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CONTENTS

Page 139 : THE NAPIER 'DELTIC' MARINE ENGINE.

147 : THE CONTROL OR GOVERNOR GEAR FOR STEAM TURBINES, *by W. Twynham, Chief Mechanical Engineer, Steam Turbine Division.*

157 : A THREE-STAGE 'MAGNAVOLT' ROTARY AMPLIFIER, *by E. A. Binney, Traction Development Department.*

160 : INSULATION OF ROTATING ELECTRICAL MACHINERY, *by E. Jones, B.Sc.(Eng.), M.I.E.E., A.M.I.Mech.E., A.M.Amer.I.E.E., Chief Insulation Engineer.*

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H.M. Fast Patrol Boat P.5212 undergoing trials with two Napier 'Deltic' 2,500 s.h.p. diesel engines

The Napier 'Deltic' Marine Engine

THE 'DELTIC' ENGINE has been designed and developed for the Royal Navy by D. Napier and Son Limited on behalf of The English Electric Company, the name 'Deltic' being derived from the triangular form in which its cylinders are disposed.

It is a diesel engine operating on the two-stroke cycle and utilising the opposed-piston principle. By the arrangement of cylinders in the form of a triangle the technical merits of efficiency and mechanical simplicity which are inherent in the opposed-piston design are exploited to the full and its disadvantages eliminated.

The components of the engine are small enough to permit the use of the most modern aero engine materials and manufacturing techniques, and this has made possible the use of such items as fully hardened crankshafts, thin-wall lead-bronzed bearings and case-hardened and ground gears, which at the designed ratings give extremely long life.

Fig. 1. Napier 'Deltic' 2,500 b.h.p. engine, from free end showing scavenge blower

The embodiment of the foregoing major features in the design has produced a power unit which is outstanding for its compact form, low weight, mechanical reliability and ease of maintenance.

The 'Deltic' is made as a self-contained power plant with all the required pumps and filters, and the control of both engine and reverse gear is effected by a single lever. Two views of the engine are shown in Figs. 1 and 2. All drives for camshaft, pumps, scavenge blower and other auxiliaries are taken from the driving end.

All parts of the engine, both individual components and major assemblies such as the reverse gear, phasing gear and scavenge blower, are so manufactured as to be fully interchangeable, and this has allowed the principle of 'repair by replacement' to be adopted as a fundamental feature of the design, thus reducing periods of unserviceability to a minimum.

Although produced in the first instance for marine propulsion purposes, the technical merits of the engine open up a wide range of uses in other fields.

This article describes the 18-cylinder Deltic engine which is now in production by D. Napier and Son Limited, but a 9-cylinder version of the engine is also being produced maintaining the triangular form but using three-throw crankshafts.

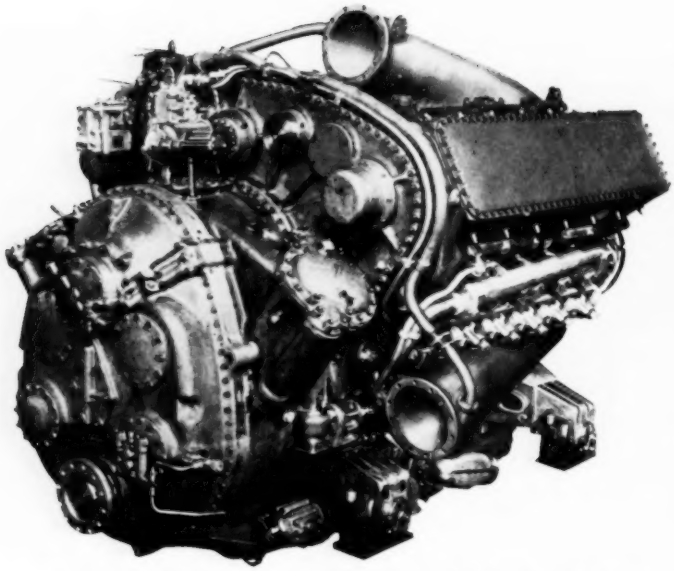


Fig. 2. Napier 'Deltic' 2,500 b.h.p. engine, from driving end showing reverse gearbox

Leading Technical Data

The leading technical data of the 18-cylinder Deltic engine are :—

Shaft horse power :

Maximum ..	2,500 at 2,000 crankshaft r.p.m.
Continuous ..	1,875 at 1,700 crankshaft r.p.m.

Nett dry weight :

Engine only ..	8,725 lb = 3.5 lb per h.p.
Engine with reverse gear ..	10,500 lb = 4.2 lb per h.p.

Overall dimensions :

Length (engine and reverse gear) ..	10 ft 11 in.
Width	6 ft 2⅛ in.
Height	7 ft 1 in.

Cylinder data :

Cylinder bore	5⅛ in.
Stroke	7¼ in. × 2.
Swept volume, total ..	5,384 cu. in. (88.3 litres).
Swept volume, effective	5,300 cu. in. (86.9 litres).
Piston speed at 2,000 r.p.m.	2,416 feet per minute.
B.M.E.P. at maximum power	91.9 lb per square inch.

Cylinder Layout

The outstanding feature of the engine is the disposition of the cylinders, in cross section in the form of an equilateral triangle as illustrated in Fig. 3. With this arrangement it is noteworthy that one crankshaft (in practice the bottom one) must rotate in the opposite sense from the other two. Two important technical advantages arise directly from this geometrical layout.

Firstly, there results automatically a phase angle difference of 20° between exhaust and inlet crankshafts, this phase displacement, with the exhaust crankshaft leading, permitting the use of an extremely efficient porting layout for scavenging and cylinder charging.

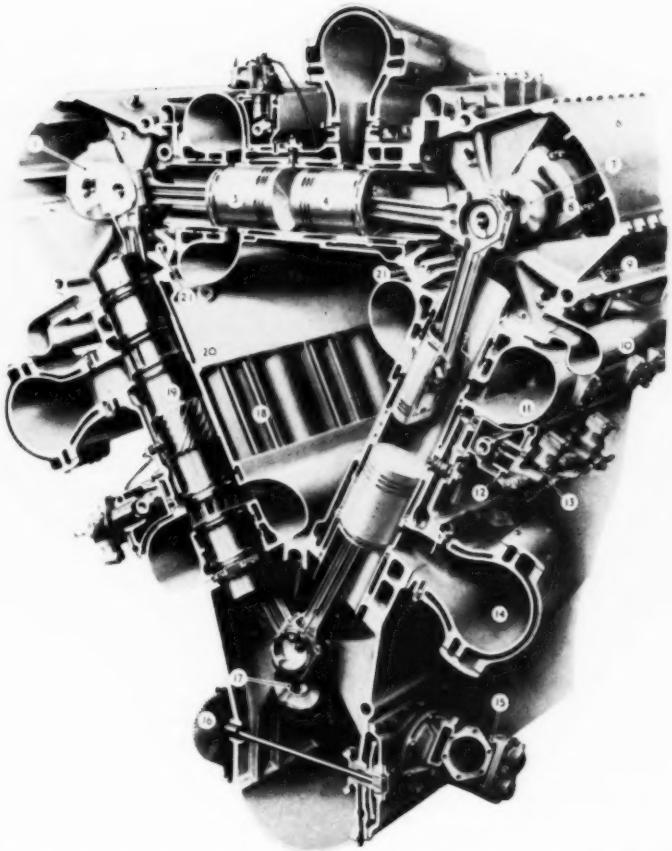
Secondly, each crankpin carries one inlet and one exhaust piston so that the loading on each crankpin, and therefore the power transmitted through each crankshaft, are identical.

When this triangular arrangement is extended through the length of the 6-throw crankshafts, each shaft having a normal cylinder firing order of 1, 5, 3, 4, 2, 6, the resultant 18-cylinder engine has equal firing intervals of 20°, this giving extreme smoothness in running.

Construction of the Triangle

The patented triangulated unit which constitutes the main body of the engine is built up from three identical cast aluminium 6-cylinder blocks forming the sides, and three cast aluminium crankcases at the corners, the two upper cases being essentially identical but the lower one being deepened in section to carry engine bearers and to provide effective oil drainage.

The resulting structure is held together by high tensile steel through-bolts extending from each crankcase through the cylinder block to the other crankcase. These bolts carry all combustion loads, the cylinder blocks remaining in compression.



1 Crankshaft for ' B ' and ' C ' Blocks
2 Crankcase for ' B ' and ' C ' Blocks
3 Inlet Piston
4 Exhaust Piston
5 Crankcase Breather
6 Crankcase for ' A ' and ' B ' Blocks
7 Crankshaft for ' A ' and ' B ' Blocks
8 Main Bearing Cap
9 Crankcase Tie-Bolt
10 Drain Oil Manifold
11 Air Inlet Gallery
12 Camshaft Casing for ' A ' Block
13 Fuel Injection Pump
14 Exhaust Manifold
15 Sea-Water Pump
16 Fresh-Water Pump and Pressure-Oil Pump Drive Gear
17 Crankshaft for ' C ' and ' A ' Blocks
18 Cylinder Block Tie-Bolts
19 Cylinder Liner
20 ' C ' Cylinder Block
21 Blower Flexible Drive Shafts

Fig. 3. Section through No. 5 cylinder, viewed from driving end

This triangular unit is therefore extremely strong and inherently of great rigidity.

Cylinder Liners

The cylinder liners are of the ' wet ' type and are machined from hollow steel forgings, an external view being shown in Fig. 4. Liners are located in the blocks at one end, and water seals are made by rubber sealing members. The bores of the liners are chromium plated and are finished by lapping.

Exhaust ports are machined around approximately half the circumference at one end, the bars between the ports being water cooled.

Inlet ports at the other end are provided around the whole circumference and are machined with a partly tangential direction of entry, thus imparting a ' swirl ' to the inlet air which assists the scavenging process and which is utilised to obtain efficient mixing of fuel and air in the combustion chamber.

Injection System

Two injectors are provided for each cylinder.

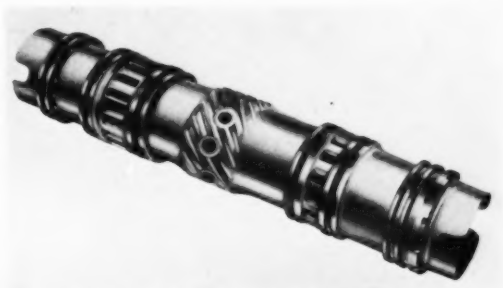
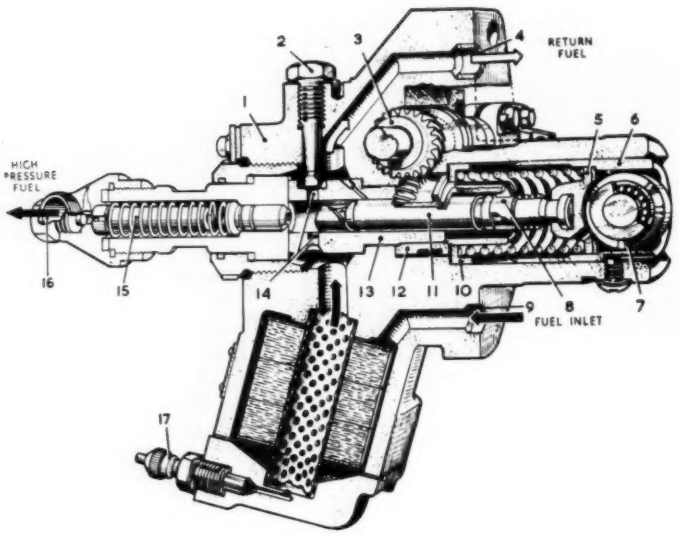


Fig. 4. External view of cylinder liner



1 Injection Pump Housing
2 Barrel Locating Bolt
3 Control Rod Gear
4 Return Line Duct
5 Lower Spring Plate
6 Tappet Shell
7 Tappet Roller
8 Plunger Dog Clutch
9 Supply Line Duct
10 Upper Spring Plate
11 Plunger
12 Control Sleeve
13 Pump Barrel
14 Fill and Spill Ports
15 Delivery Valve
16 Fuel Outlet Tee-Piece
17 Schrader Air Release Valve

Fig. 5. Fuel injection pump

These are of the outward-opening valve type and both injectors are fed with fuel from a single injection pump.

The nozzles inject at a wide angle from the axis of the injectors, thus delivering fuel at the outer edge of the combustion chamber, the fuel being transported to the centre by virtue of the air swirl previously mentioned.

The pumps are of normal C.A.V. type modified to suit the design requirements of the engine, and are as illustrated in Fig. 5. The six pumps for each cylinder bank are carried on a camshaft casing extending the length of the cylinder block, all three camshaft casings being interchangeable. Rack control is by a rotating shaft, pumps being connected together by small couplings which are torsionally stiff but axially flexible, thus eliminating differential expansion effects.

Arrangements have been made in the design to allow any one pump to be removed and replaced by another, correct timing and matching being automatically obtained.

Fig. 6. Piston components

Pistons

The special patented pistons are constructed of two parts held together by a spring circlip, these components being shown in Fig. 6.

The inner member is machined from a Y alloy forging and carries the hardened steel gudgeon pin which is fitted tightly in it.

The outer member is of cast aluminium having an unbroken skirt and is provided with a cast-in austenitic iron insert in which the two top gas rings are mounted.

Between the outer and inner members is an annular chamber extending from the bottom of the skirt to behind the gas rings and thence by grooves

in the top face of the inner member passing across the underside of the piston crown. Oil is fed into this chamber from the connecting rod for cooling purposes, escape holes being provided in suitable positions so that cooling is effected by the 'cocktail shaker' method augmented by continuous flow.

Connecting Rods

Connecting rods are manufactured from high tensile steel stampings and are machined and polished all over. The pairs of rods on each crankpin are of the 'fork and blade' type, views of these, together with details of the big-end assembly, being given in Fig. 7.

The big end of the forked rod is fitted with a steel shell nitrided on its outer surface and carrying in its bore a Vandervell steel strip bearing, lead bronze lined and lead plated, which runs direct on the crankpin. The outside surface of the shell provides the bearing surface for the blade rod, the big end of which is also fitted with a steel strip lead bronzed and lead coated bearing.

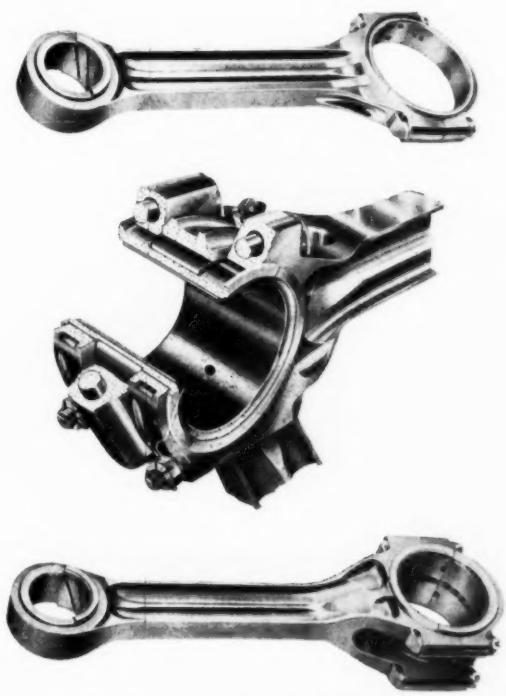


Fig. 7. Connecting rods and big-end assembly

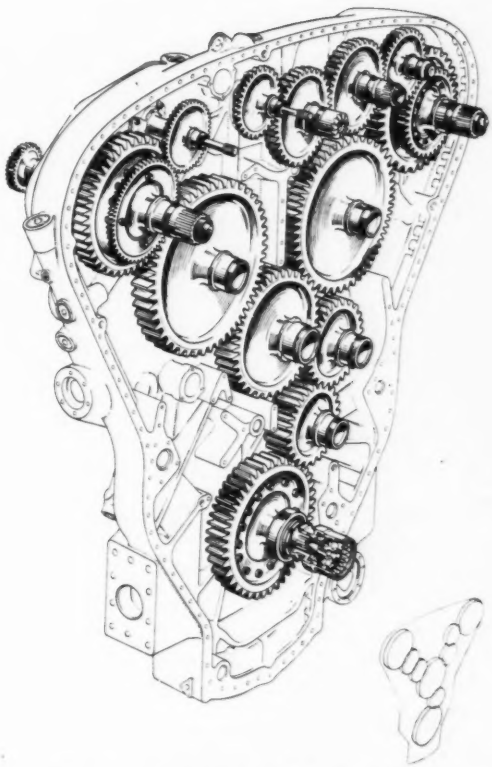


Fig. 8. Arrangement of phasing gearing

The small ends of both rods are also equipped with steel strip lead bronzed bearings.

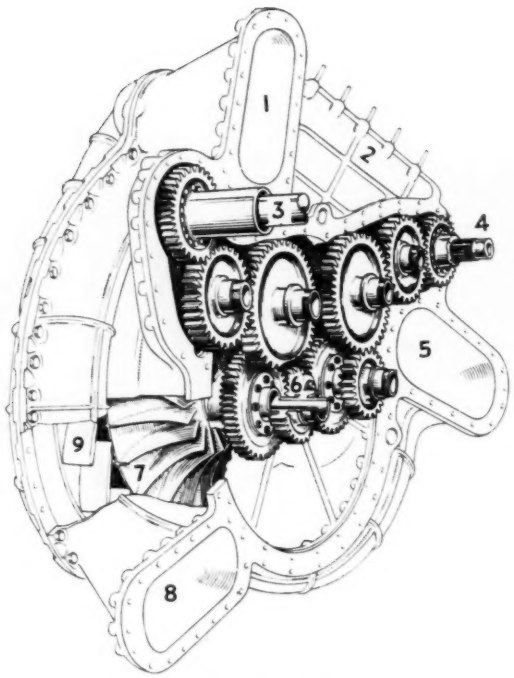
Both rods are rifle drilled for the purpose of feeding oil from the crankpin for small-end lubrication and for piston cooling.

Crankshafts

The seven-bearing crankshafts are nitrided all over, the bearing surfaces being finished by lapping.

The main journals run in steel strip lead bronzed and lead plated bearings which are carried direct in the cast aluminium crankcases. Oil is supplied to each journal through oil galleries extending the length of the crankcases and thence through passages in the crankshafts to the crankpins.

The three crankshafts are coupled together



1 Outlet to ' B ' Cylinder Block
2 Air Inlet
3 & 4 Flexible Drive Shafts
5 Outlet to ' A ' Cylinder Block
6 Impeller Drive Pinion
7 Impeller
8 Outlet to ' C ' Cylinder Block
9 Diffuser Ring

Fig. 9. Scavenge blower and drive

through a gearing system as shown in Fig. 8, the power from each crankshaft being transmitted through a tributary gear train into a common output shaft at the centre of the triangle, this shaft running at slightly above crankshaft speed. The connection between each crankshaft and its gear train is made through a flexible quill shaft.

By alternative assemblies of idler gears in this phasing system the output shaft rotation can be reversed, the crankshaft rotation remaining unchanged, this providing a method of meeting the requirement for engines having ' handed ' rotation.

Lubrication and Cooling

All bearings and gear meshes throughout the engine are supplied with oil under pressure, the system being of the ' dry sump ' type in which oil is returned to the tank by a scavenge pump. A sea-water cooled heat exchanger is included in the scavenge circuit for oil cooling purposes, thermostats being provided to control the oil temperature.

The cylinder jackets form part of a closed system in which distilled water is circulated through a heat exchanger by a centrifugal pump on the engine. Sea water is circulated through the cool side of the heat exchanger by a gear-type pump, and thermostatic temperature control is provided.

Scavenge Blower

Scavenge air for the engine is supplied by a single stage, double sided, centrifugal-type blower. The impeller is machined from a Y alloy forging and delivers air through a diffuser into a casing having three exits, one to each bank of cylinders. The blower is driven by two flexible shafts connecting with gears at the driving end of the two top crankshafts. The assembly of the blower with its gearing is illustrated in Fig. 9.

1 Input Shaft
2 Astern Drive Gear
3 Astern Idler
4 Gear-Carrier Plate
5 Free-end Casing
6 Oil Duct to Ahead Clutch
7 Centre Casing
8 Drive-end Casing
9 Clutch
10 Ahead Drive Gear
11 Ahead Layshaft Gear
12 Output Shaft-Coupling
13 ' C ' Layshaft
14 Output Shaft
15 Output Shaft Gear
16 Ahead Pinion
17 Ahead-and-Astern-Pinion
18 ' A ' Layshaft

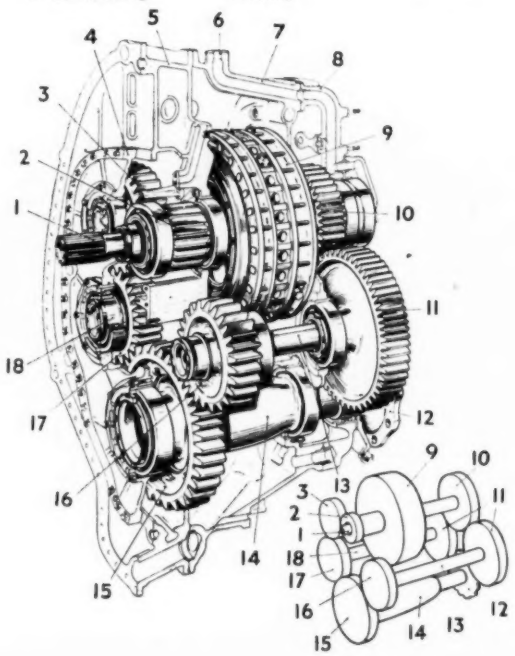


Fig. 10. Arrangement of gears in reverse gearbox

1 Connection to Governor
2 Exhaust Outlet
3 Piston
4 Return Spring
5 Clutch Jaw
6 Main Drive Shaft
7 Mounting Flange
8 Cylinder Body
9 Perforated Disc
10 Combustion Chamber
11 Exhaust Valve
12 Safety Disc

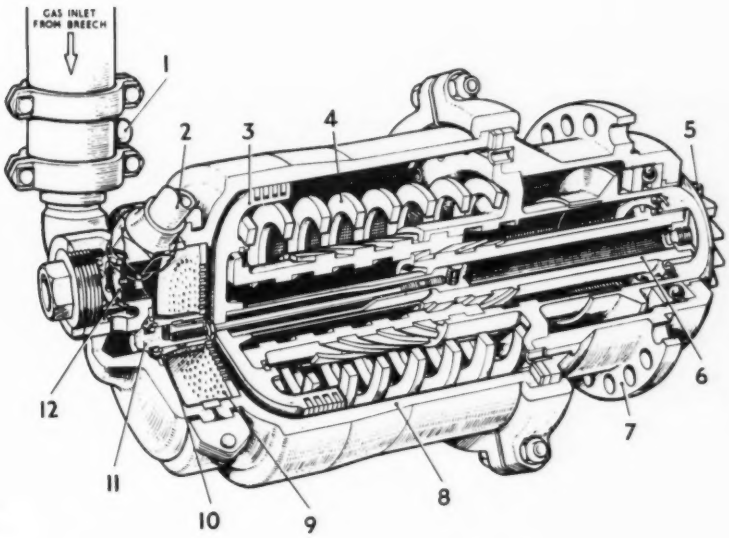


Fig. 11. *Diagram of starter*

Reverse and Reduction Gear

The reversing mechanism takes the form of two constant-mesh gear systems, one for ahead running and one for astern, the appropriate gear train being connected at will by hydraulically loaded plate clutches. The clutches are connected to the output shaft from the phasing gear train and therefore run at slightly over crankshaft speed. Controls for the clutches are interconnected with the engine power control.

The gear trains in the reversing gearbox also provide appropriate speed reductions, the crankshaft to propeller shaft gear ratios being 2.106 in 'ahead,' and 2.397 in 'astern.' An illustration of the reverse gearbox is given in Fig. 10.

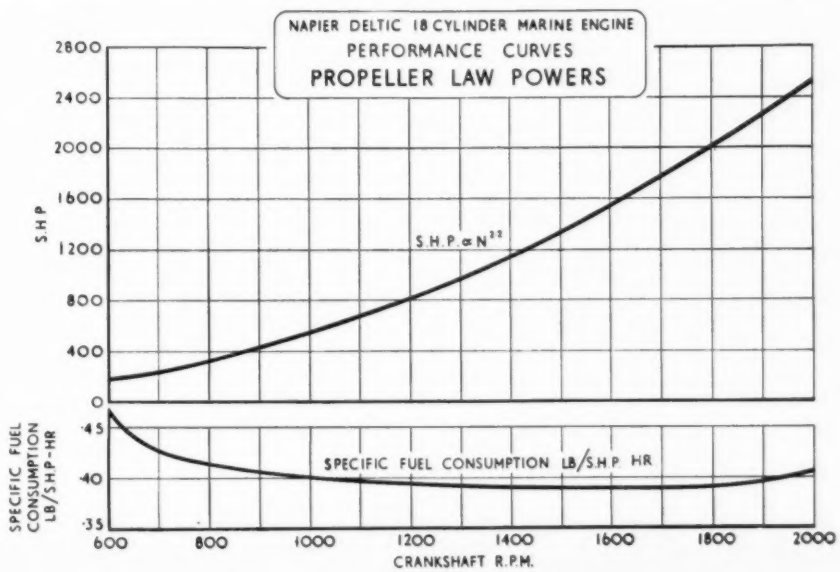


Fig. 12.
Performance curves with propeller

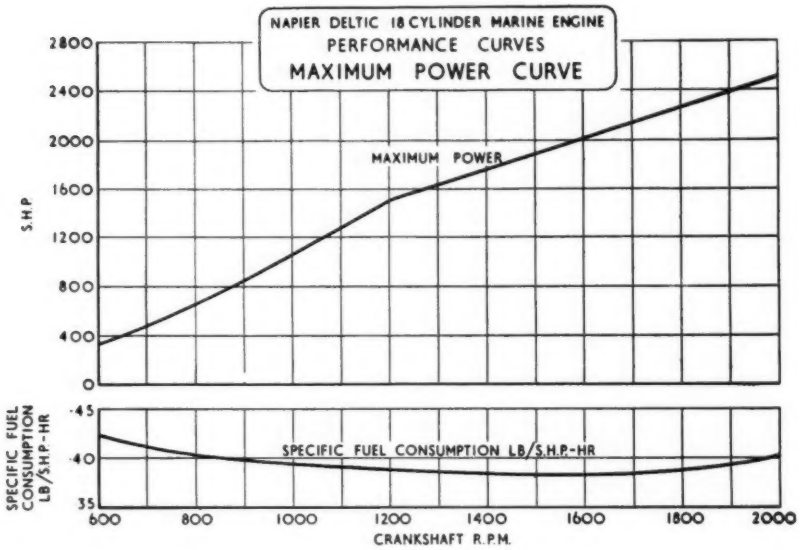


Fig. 13. *Maximum power performance curves*

Starting

The engine is started by a combustion-type starter in which a cartridge is fired into a cylinder containing a piston mounted on a helically splined shaft carrying a Bendix-type claw coupling. The starter is mounted on the phasing gear casing, its claw engaging with a similar one on a gear meshing directly with one of the upper crankshafts. A rotary breech carrying 5 cartridges which are electrically fired forms part of the starter equipment. A diagram of the starter is shown in Fig. 11.

Engine Performance

Performances of the engine when driving a fixed-pitch marine propeller are shown in Fig. 12.

The maximum power performances against speed are given in Fig. 13.

The Control or Governor Gear for Steam Turbines

By W. TWYNHAM, Chief Mechanical Engineer, Steam Turbine Division.

A STEAM TURBINE is capable of driving any type of electrical generator, and 'control gear' is the general term applied to the apparatus used to enable the turbine output to follow the generator load with adequate stability and speed of response. The design of control gear depends on the function of the turbine and generator, and different types are necessary to meet the requirements of straight condensing, extraction, and back-pressure turbines. This article, however, is confined to straight condensing turbines driving electrical alternators, since these are the most commonly used for steam power plant.

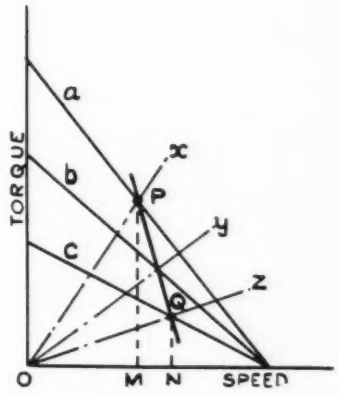
Although the general principles of control have reached a high degree of standardisation, considerable difference exists in their practical application by different manufacturers. It will therefore be of interest to study the fundamental principles and follow their application and development for modern steam turbines.

Fundamental Principles

Any change in electrical load has to be partly absorbed by the inertia of the rotating elements of turbine and alternator, and consequently some change in speed must occur. The adjustment of input to output therefore introduces consideration of the torque-speed characteristics of both the electrical load and the output from the steam turbine.

As has been shown by a previous article in this journal,* the combination of steam turbine and generator is inherently stable, and the torque-speed characteristics for a typical turbo-alternator set are shown graphically in Fig. 1.

The power developed by a steam turbine is controlled by the main steam control valve, and its opening has to be automatically adjusted to follow changes in the electrical load.



Theoretical characteristic curves of turbine (a, b & c) and alternator (x, y & z) speed 'droop' (NM) for no load (Q) to full load (P)

Fig. 1. Torque-speed characteristics for a typical turbo-alternator set

In general terms the mechanism employed is a centrifugal device or governor mechanically driven by the turbine shaft, which operates through a servo-mechanism to adjust the control valve position on change of speed.

Although speed 'droop' is necessary for the stability of load division between coupled generating sets, it is essential that the voltage and frequency be maintained as nearly constant as possible, and thus that the speed 'droop' be kept to a minimum. The British Standard is 4% and this has been determined by experience to give satisfactory results. Furthermore, a 'change in speed' device is

*H. G. Yates. *The fundamentals of steam turbine governing.* E. E. Journal (June 1941) Vol. X No. 3, p76.

necessary to correct frequency fluctuations and for synchronising.

The ideal of maximum efficiency at all loads would require the adjustment of the steam passage areas of all stages to suit the varying steam quantity. Since this is obviously not practicable for constructional reasons, two compromise methods are normally employed, namely, throttle and nozzle control.

A theoretical ' Willans Line ' showing the steady-state relation between load and steam quantity is shown in Fig. 2 for a turbine controlled by three steam admission valves. These operate sequentially to produce 60%, 80% and 100% load.

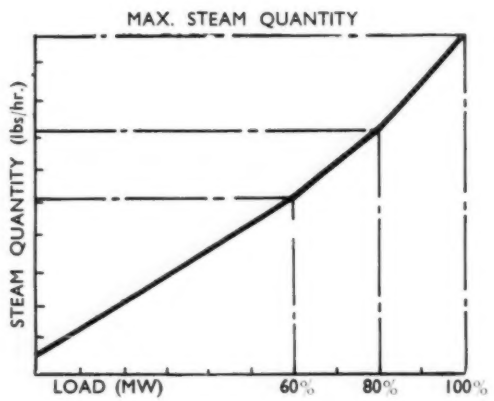


Fig. 2. Theoretical ' Willans Line ' showing the steady-state relation between load and steam quantity

There is also a relationship between steam quantity and valve travel which should approximate to a straight line as far as possible. Undue discontinuity of the slope occasioned by excessive valve clearances or badly worn seatings can result in operational difficulties when valves are beginning to open, particularly when synchronising.

Throttle and Nozzle Control

Fig. 3 (*a*) shows a diagrammatic arrangement for a single throttle valve control where all nozzles are

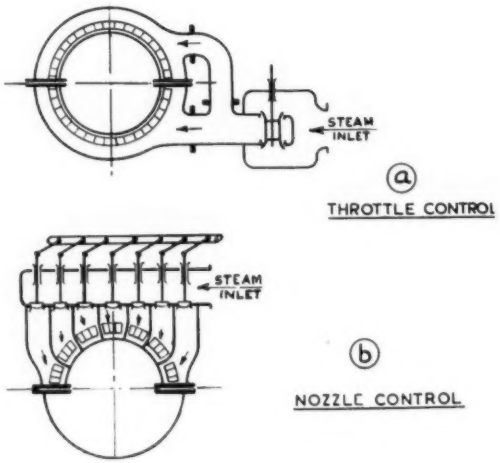


Fig. 3. Diagrammatic arrangement of throttle and nozzle control

open to steam whatever the load, whilst Fig. 3 (*b*) shows diagrammatically a multi-nozzle batch arrangement where each batch is under control of individual governing valves arranged to open

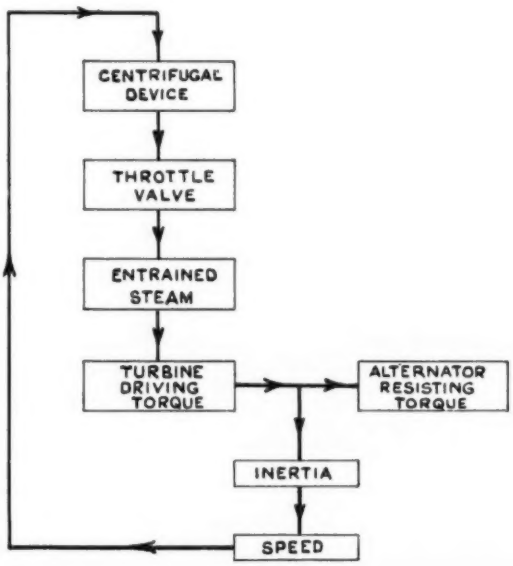


Fig. 4. Simplified block diagram showing basic sequence of steam turbine regulation

automatically in succession. Whilst the latter will give a small improvement in steam consumption at partial loads, the additional complication of the control gear to operate a large number of nozzle control valves is not justified unless it is intended to operate the machine at light loads for lengthy periods. In addition, partial admission tends to encourage blade vibration with consequent risk of blade failures.

The simplified block diagram in Fig. 4 shows the basic sequence of steam turbine regulation. It is evident that automatic control is essential to attain the requisite degree of performance, and the development of suitable mechanisms will now be considered.

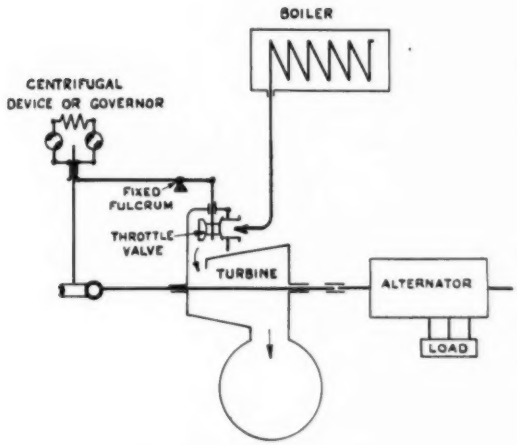


Fig. 5. Direct-acting control gear

Direct Acting Control Gear

The simplest form of control gear is shown diagrammatically in Fig. 5, where the centrifugal device supplies the power for direct operation of the throttle valve. This arrangement has been satisfactory for small turbines operating with low steam conditions, where the unbalanced forces to be overcome are relatively small.

Mechanical Oil Relay Gear

For large turbines operating under modern steam conditions, considerable power is required to move the valves and it is general practice to interpose a displacement transmission mechanism with force amplifications, as shown in Fig. 6. This consists of a centrifugal device or governor A coupled to an oil distribution valve C, a servo-motor or relay piston D and a compensating or feed back lever F. On change of speed, movement of governor A displaces the valve C which applies oil pressure to one side of the piston D and simultaneously opens the other side to drain. Under steady conditions, the valve C must be in its central position and thus the compensating lever F causes the movement of the steam valve to be proportioned to the speed change.

This simple arrangement has two main disadvantages. Firstly, physical limitations are imposed by the compensating lever since it makes it necessary for the governor and servo-motor to be close together. Secondly, the power required from the governor to operate the mechanism is still unduly large and this necessitates a centrifugal device of heavy construction rotating at a comparatively slow speed ; such a construction has a relatively slow response and consequently reduces the rapidity of action of the entire control gear.

Whilst this gear has proved satisfactory for intermediate steam conditions, the advent of elevated steam conditions together with increased steam quantity required an improved type of control gear, due to the considerable increase in unbalanced steam forces on the main valve and the faster response demanded by the lower inertias of rotors.

Typical Modern Control System

Fig. 7 shows a diagrammatic arrangement of the improved control gear. The centrifugal device or governor A is driven direct from the turbine shaft by helical gears and is mechanically connected to the oil governing valve D operating in the primary relay B, the latter being hydraulically connected with the secondary relay C. The centrifugal device runs at high speed and its degree of sensitivity is conferred on the control gear as a whole by virtue of the subsequent two stages of amplification.

From Fig. 8 it will be seen that the displacement of the centrifugal device (*a*) is transmuted to a hydraulic oil pressure characteristic (*b*) which is transmitted to the secondary relay to determine the opening of the steam valves and consequently the load on the machine (*c*).

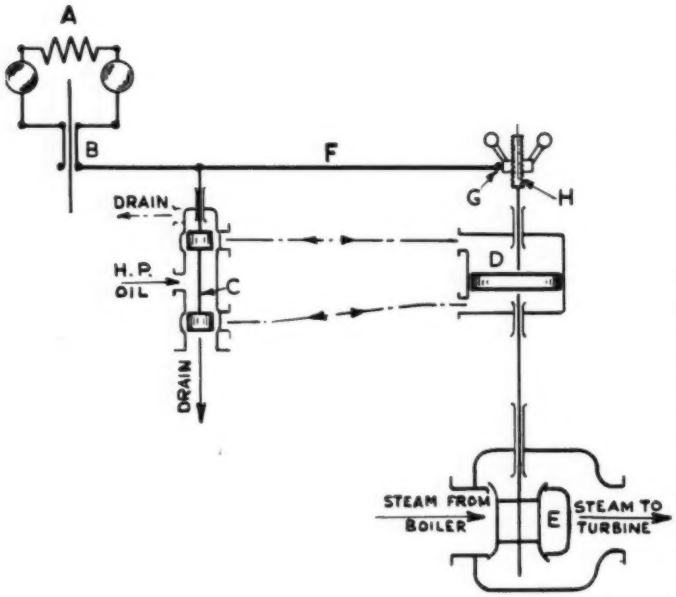


Fig. 6. Mechanical oil-relay control gear

Displacement of the centrifugal device A (Fig. 7) is transmitted to the oil governing valve D which momentarily moves in relation to the bellows sleeve F. The position of the latter is controlled by the hydraulic pressure imposed on the unbalanced annular area and the opposing spring H which are in equilibrium under steady-state conditions. This condition, coupled with the controlling exhaust restriction between D and F at G, produces an oil pressure which decreases as the speed increases and *vice versa*. The flow of oil is determined by the pressure and the regulating valve J. Changes in pressure are rapidly transmitted by the hydraulic system to the secondary relay C, where the spring loaded bellows K transforms

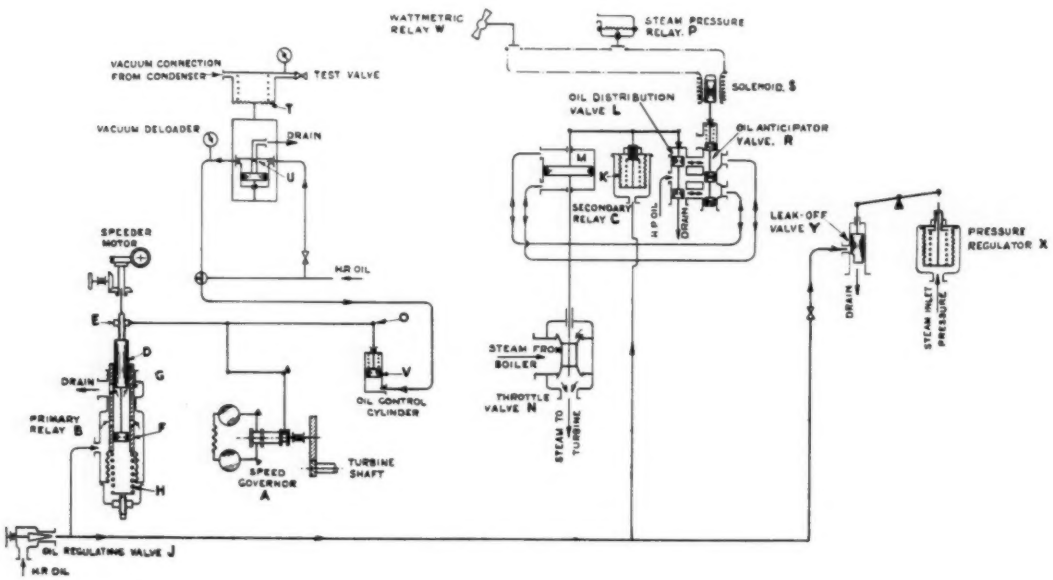


Fig. 7. Diagrammatic arrangement of modern control system

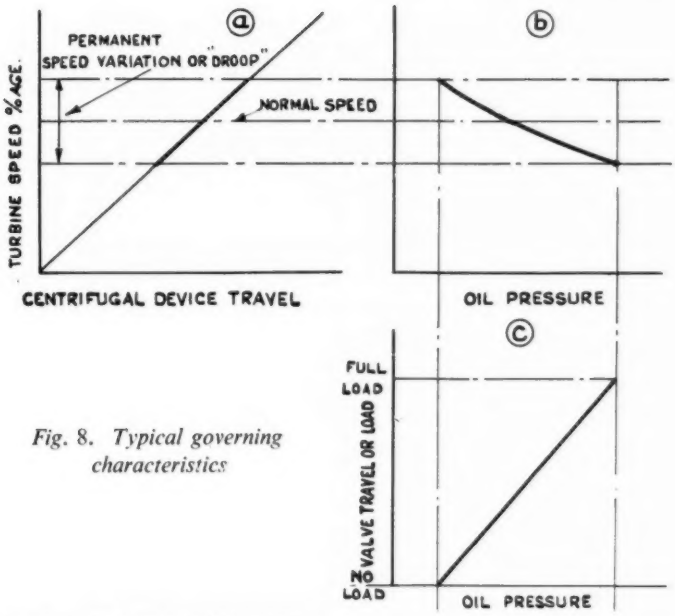


Fig. 8. Typical governing characteristics

the pressure into a displacement. The latter operates the main throttle valve N by the combination of the oil distributing valve L and the servo-motor M.

An appreciation of this control system and its basic motions can readily be made from the comprehensive block scheme in Fig. 9.

Among the many advantages gained with this improved control gear, the following are of particular interest :—

(1) The introduction of a high-speed centrifugal device allows a direct drive through helical gears and eliminates the possible troubles arising from the use of worm gears.

(2) Since it is followed by two stages of amplification, the centrifugal device is small. Hence a light design of low inertia can be employed with consequent improvement in sensitivity and rapidity of response.

(3) The hydraulic transmission confers complete freedom in the position of the steam chests.

(4) Adjustments to the various controls are relatively simple.

(5) The compact centrifugal device and primary relay are completely housed in and protected by the steam-end pedestal, but at the same time are easily accessible.

(6) It is readily adaptable for multi-valve operation due to the flexibility of the hydraulic system.

From the foregoing it will be seen that the requirements of modern turbines have been met by progressive development of the

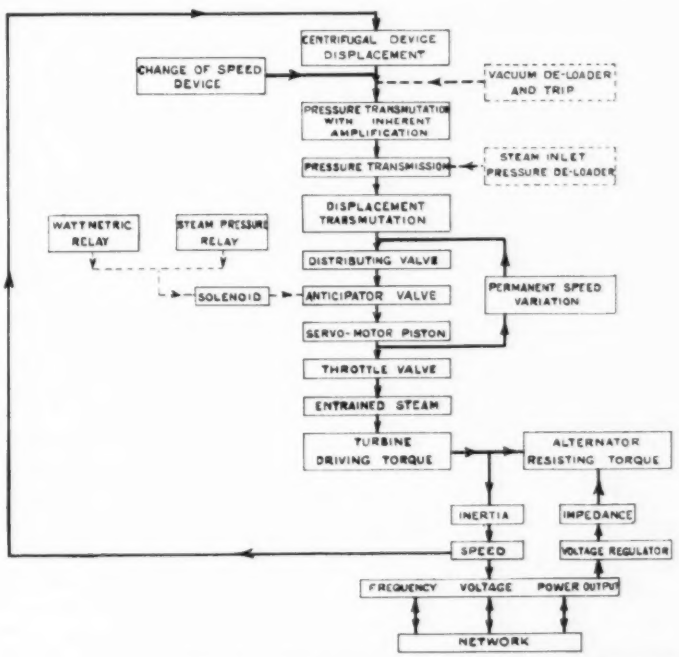


Fig. 9. Block diagram for mechanical-hydraulic control gear, including vacuum and steam inlet pressure de-loaders and governor anticipator

control gear, and the next stage may well be in the direction of electrical frequency governors, which show distinct possibilities of application to steam turbines.

Good governing can be achieved only by correctly combining the individual characteristics of a number of components, and it will therefore be of interest to consider the development of some major items in the control system.

Centrifugal Devices

The centrifugal device is the primary component and its essential features are reliability, sensitivity and relatively large power in a small space. Successive improvements have been made since James Watt's original design to reduce inherent friction to a minimum and thus eliminate hunting across the ' dead band ' with its consequent instability.

The centrifugal device now employed by The English Electric Company is shown in Fig. 10. The weights A are carried on bell-crank levers L and support the springs S in conjunction with collars which are easily adjustable during assembly and test. Ball races are fitted at joints subject to rotational movement, and since the springs directly oppose centrifugal force, the levers have only to transmit the small operating energy required from the centrifugal device. High-speed centrifugal devices of this type have been proved on test to give a ' dead band ' of only 0.1 to 0.2% over the full travel, whilst the transient incremental ' dead band ' is as low as 0.05%.

Governing Valve Assemblies

Experience has shown that advancing steam conditions have created new problems in fluid mechanics and metallurgy. The two main problems have been firstly, valve vibration due to the heavier dynamic forces caused by the flow of denser steam, and secondly, differential expansion between the valve and seats.

The first problem involved wear on both spindles and gland bushings, rendering replacements necessary at frequent intervals. Investigations made in The English Electric Company's Air Flow Laboratory showed that the vibration could be practically eliminated by substituting drilled holes (Fig. 11a) for ports (Fig. 11b) in the valve cage, and that further improvements could be obtained by internal steam flow (arrows X), as compared with external flow (arrows Y). The results of these tests have been substantiated by operating experience.

Whilst the absence of vibration eliminates frettage between the valve spindle and guide bushes, it is inherent that the spindle makes contact somewhere in the guides ; hence there is possible risk of seizure with consequent failure of governing. In order to avoid this, many combinations of alloy materials for the spindles and bushes have been tried and, whilst stainless spindles with nickel alloy bushes have been satisfactory in the past, it has been found that for modern steam conditions it is advisable to use nitrided steels.

General standard practice has been to use double seated governing valves. Since it is impossible to guarantee perfect seating on top and bottom seats, a condition of seat erosion has developed with increasing steam conditions with consequent inability of the valves to shut off steam when nominally closed. This is further aggravated by the use of materials for valves and cages which have different coefficients of linear expansion.

The introduction of stellited valves and seats has been found to eliminate steam or water erosion, and differential thermal expansion is reduced by using identical materials.

In order to avoid the difficulties experienced with the double seated valves and to ameliorate synchronising with elevated steam conditions, it would appear desirable to use smaller valves of the single-seated mushroom type. This type of valve is unbalanced and consequently necessitates greatly increased operating forces from the main servo-motor. To meet this requirement and ensure rapid closing of the valves, the relay oil pressure would be increased.

Oil Pumps

General steam turbine practice is to use lubricating oil for operating the servo-motors, and for this purpose oil is supplied from the pump (at relay pressure) direct to the servo-motor, and the pressure suitably reduced for lubrication. The pumps are usually of the positive displacement gear type which, for many years, were driven by worm gearing from the turbine shaft, but as turbine sizes and consequently pump capacities increased and imposed heavier duties on the drive, it was

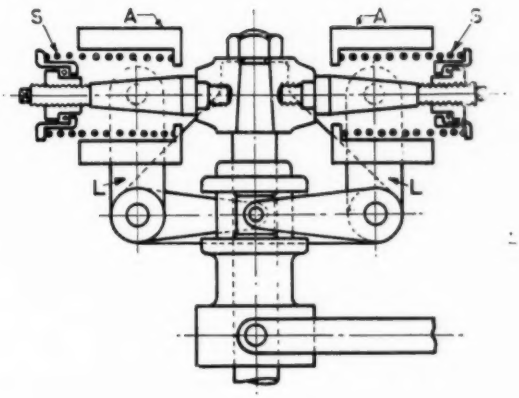


Fig. 10. *Centrifugal device or governor*

difficult to obtain a satisfactory operating life of the worm gears. This trouble was overcome by the introduction of a direct drive through helical gears and running the pumps at a higher speed.

With a gear pump it is essential that clearances are small to maintain efficiency. This limits the allowable clearances in the bearings and makes them susceptible to seizure if any foreign matter is present in the oil, even after the most rigid cleansing of the system. In addition, the increase in oil quantities and pressures imposes heavy loading on the bearings, which can only be met by considerable increase in size, and for machines of 100 MW capacity such pumps would be difficult to accommodate. Thus it will be advisable to employ yet another type of pump for the larger units.

Speed Adjusting Gear

When a set is running alone, load changes are automatically controlled by the centrifugal device within the limits defined by the speed variation, but it is necessary to include some form of speed adjustment when on load or at no-load for synchronising.

In Fig. 6 the displacement for this is directly added to the return motion from the servo-motor piston by the rotation of the nut G on the thread H. As the oil valve C will be in its neutral position under steady-state conditions, it is virtually a fixed fulcrum and movement of the nut is followed by a corresponding movement of B.

In the case of the modern control system, Fig. 7, the change-of-speed displacement is inserted into the control sequence at the nut E.

This speed adjustment can be done either by hand at the turbine, or electrically by remote operation from the control room.

With the larger power networks in existence to-day, all major alternators run at the same steady speed since they are electrically coupled. If, under such conditions, the driving torques from the

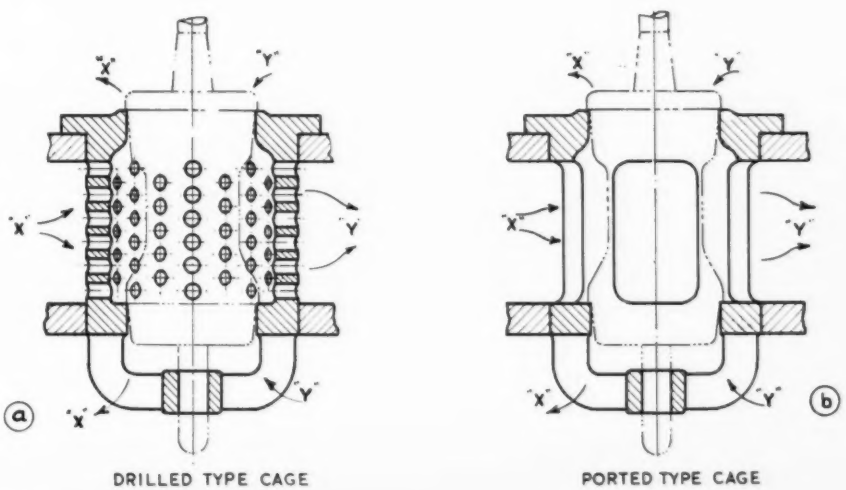


Fig. 11. *Governing-valve cages of the drilled and ported types*

turbines are insufficient to meet the load demand, then the system frequency will fall and the load on each machine will increase according to the speed-load characteristic of its governor. The consequential load sharing may be materially different from that originally arranged or intended, and therefore the control gear must allow adjustment of load on individual machines. This is done by operating the speed adjustment gear, which under such conditions is in effect load controlling gear. As the centrifugal device is virtually fixed for any given speed, movement of the speeder gear of a single turbine gives a corresponding movement of the steam valves.

Entrained Steam

The steam which is located at any instant between the control valve and the last stage of the turbine ('entrained steam') introduces a severe time delay into the regulation. This is very apparent if a sudden drop in load occurs and the synchronising tie is broken, when even if the control valve closes instantaneously the ensuing expansion of the entrained steam will cause appreciable overspeeds. Overspeeds attained in practice are due to this effect, coupled with the inherent time delay of the control gear.

The major effect of entrained steam on speed rise is produced whilst the valves are closing, and is shown on the typical speed curves in Fig. 12, from which the importance of valve closing times can be appreciated. It follows, therefore, that rapid response of the control gear is essential to reduce speed rise as far as possible, since this is a factor which has been made more difficult by the increase in output and steam conditions.

Protective Devices

When considering the design of any type of mechanical device, the possibility and consequences of its failure to operate must be borne in mind, and apparatus must be fitted to mitigate the results of such failures.

In the case of a steam turbine, the failure of the control gear may result in full or partial steam supply being maintained after the electrical load has been removed due to any cause, and the ultimate consequence of a dangerous overspeed may be disastrous.

EMERGENCY TRIPS

The fitting of a centrifugal overspeed device embodied in the turbine shaft, and its associated mechanism, is the invariable practice on steam turbines. This is quite independent of the main speed governor and will shut off the steam supply should the machine reach a predetermined overspeed. As is well known, the operation of the trip mechanism is arranged to close both the emergency stop valve and the governing valves. This is done by mechanical linkage, oil relay, or a combination of the two.

For emergency conditions, provision is made to hand-trip the gear independently of the overspeed trip, or alternatively an electrical solenoid may be fitted for this purpose, allowing remote operation from the control room or by electrical protective devices.

In addition to the use of duplicate centrifugal overspeed devices to cover the possibility of one failing to operate, a further 'back-up' protection favoured by some engineers takes the form of an electrical overspeed device. This consists of a tacho-generator driven from an extension of the centrifugal device spindle, the output of which is fed to an overspeed relay. This is arranged to energise tripping relays which initiate tripping functions including the energising of the trip solenoid. The overspeed relay is set to trip when the input from the tacho-generator reaches a value corresponding to the predetermined overspeed.

GOVERNOR ANTICIPATORS

If the control of the steam valves is left to the centrifugal device, they will not close, even in the ideal case of instantaneous response, until the speed has risen by the amount of permanent speed variation (approximately 4% for full load). Therefore on loss of full load the total overspeed will be the sum of the permanent speed variation plus the additional speed rise due to stored steam. To avoid excessive overspeed it is essential to close the steam valves in the shortest possible time by the use of a device which will anticipate the governor operation and close the steam valves at practically normal speed.

An arrangement to meet this requirement is shown in Fig. 7, where the energising circuit for the solenoid S is completed by the contacts of a

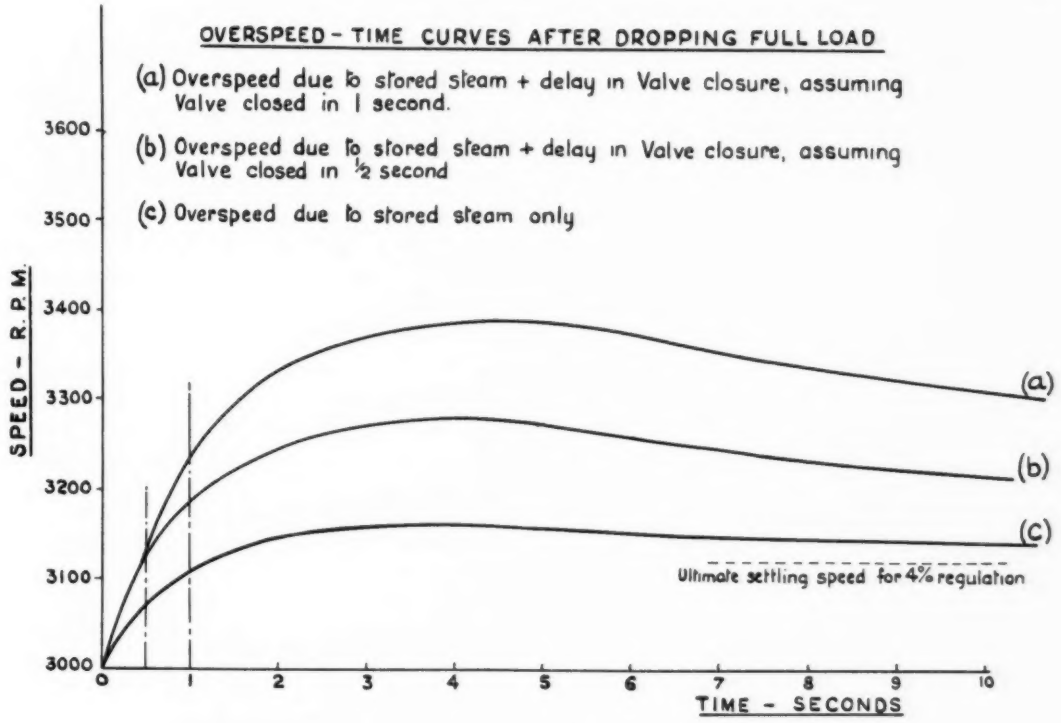


Fig. 12. Typical speed curves, showing the effect of entrained steam

wattmetric relay W and a steam pressure relay P under predetermined conditions of operation.

The wattmetric relay is arranged so that its contacts are closed below some suitable low value of load, and are open for values above this setting. The steam pressure relay contacts are closed only when the steam pressure is above a value corresponding to about 50% of full load. Thus the energising circuit will be completed only when there is a combination of high steam pressure and low load, such as would occur on a sudden load reduction from above the value corresponding to the steam pressure relay setting to a value below the wattmetric relay setting. With these conditions prevailing, the solenoid displaces a plunger causing the oil valve R to operate the servo-motor piston M which immediately closes the steam valves. For all other conditions either one or both sets of contacts will be open to make the gear inoperative and permit normal loading or de-loading of the machine.

An alternative scheme employs an acceleration-sensitive device in addition to the centrifugal device. On loss of load, the acceleration-sensitive device anticipates the action of the centrifugal device in closing the valves, but does not interfere with normal operation of the control gear.

These devices have been referred to as governor ' anticipators ', but it is evident that they are simply developments of governing technique in which feed back is obtained directly from change of load before the speed has been affected appreciably. For this reason the principle is known as ' disturbance feed back '.

Vacuum De-loader and Vacuum Trip

For many years it has been the normal practice to fit atmospheric relief valves on the condenser to prevent possible damage to the turbine and condenser due to the increased pressures occasioned by loss of vacuum. With the development of larger machines the possibility of trouble consequent on

vacuum failure was considerably increased and a further protection was added which automatically de-loads the machine if the vacuum falls below a predetermined figure.

Fig. 7 shows such a device, where a flexible diaphragm T normally closes an oil leak-off valve U to maintain oil pressure under oil control piston V. When the vacuum falls below the predetermined figure, the diaphragm moves downwards and the reduction in oil pressure causes movement at O. This is added to the movement of the centrifugal device by the floating lever and influences the oil governing valve D to close the throttle valves.

An additional precaution is to fit a vacuum trip relay, which is arranged to operate at a predetermined figure relative to the minimum setting of the de-loader. The solenoid on the emergency gear is then energised and the steam valves are tripped.

Steam Inlet Pressure Control

With modern turbines operating on the unit system of boiler and turbine there is a possibility of trouble due to boiler priming if the steam pressure is suddenly reduced by loss of firing in the boiler or other causes. To protect the turbine from consequent carry-over it is desirable to instal a steam inlet pressure regulator superimposed on the governor control system and arranged to de-load the machine by closing the steam valves. The regulator will commence to operate and reduce load when the steam pressure falls to a predetermined figure below normal and will continue to reduce load until equilibrium is restored, to meet the steam generation in the boiler, or if necessary, until the load is a minimum as determined by the characteristics of the pressure regulator. Fig. 7 shows such a device, where the pressure regulator X functions to open the oil leak-off valve Y, thus reducing the governing oil pressure to close the throttle valves.

Conclusion

In the space available it has not been possible to deal exhaustively with any particular section of the subject, but enough has been written to show how increasingly important control gear problems are becoming with the rise in outputs and steam conditions on modern steam turbines.

The replacement of the centrifugal device control by electrical frequency control may eventually prove more convenient with machines coupled to large electrical systems, if only because of the greater simplicity this promises in effecting central control and load sharing.

Present practice of combining the lubricating and control fluids is not ideal, and further developments may result in separate systems and fluids being used for these purposes. The practice in regard to oil pumps is at the moment receiving full consideration, and developments await the results of further operating experience.

Above all, the difficulty of protecting not only the turbo-alternator set but also the boiler plant when inadvertent complete loss of load occurs, presents a problem which has not yet been completely solved, and leaves abundant scope for thought and ingenuity by engineers in the future.

A Three-Stage 'Magnavolt' Rotary Amplifier

By E. A. BINNEY, Traction Development Department.

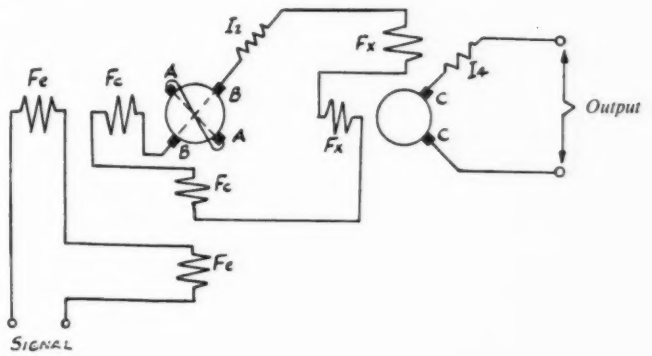


Fig. 1. Connections of 3-stage 'Magnavolt'

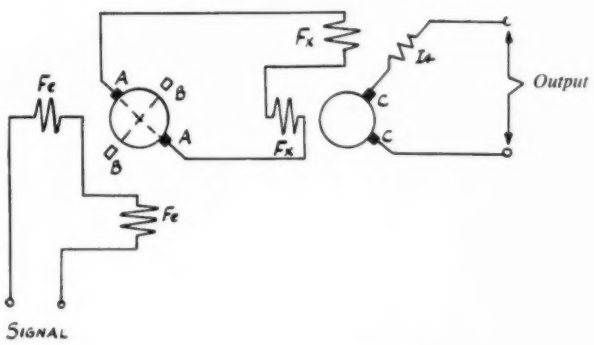


Fig. 2. Connections of 2-stage 'Magnavolt'

An interesting three-stage 'Magnavolt' rotary amplifier has recently been built by The English Electric Company. It probably represents one of the first three-stage rotary amplifiers developed, although a machine of this type was experimentally tested by this Company several years ago. The present machine was made for the University of Birmingham in collaboration with Professor A. Tustin and is so constructed that it may be operated as:—

(1) a normal two-stage 'Magnavolt',

(2) a metadyne or amplidyne,

(3) a three-stage 'Magnavolt'.

The 'Magnavolt', metadyne and amplidyne are all well-known rotary amplifiers of the two-stage type.

The three-stage 'Magnavolt' combines the principles of the two-stage 'Magnavolt' and the metadyne. The use of the expression 'metadyne'* is in the now accepted sense that the armature reaction is only partially compensated.

The internal connections of a three-stage 'Magnavolt' are shown in Fig. 1.

Armature Windings

The armature has two windings, one of 'p' poles and a second of '2p' poles. For outputs up to 10 kW, 2-pole and 4-pole windings are provided. Each winding has a commutator, the two commutators being placed at opposite ends of the armature core. In Fig. 1 each commutator and armature winding is represented by a circle; that on the left is the 2-pole winding and the other is the 4-pole winding.

* *See 'Direct current machines' by A. Tustin, p. 178.*

Magnetic Circuit

The magnetic circuit includes four mechanical poles placed at 90° intervals. Two adjacent poles form a single magnetic pole of one polarity in the 2-pole magnetic circuit and a pole pair of opposite polarity in the 4-pole magnetic circuit. In Fig. 1 the 2-pole field system is shown associated with the left hand (2-pole) armature winding; the 4-pole field is associated with the right hand (4-pole) armature winding.

The brushes A A and C C are shown in the neutral axes of both magnetic circuits, while brushes B B are shifted at 90° to the brushes A A and therefore lie in the 2-pole magnetic axis. Two interpoles are placed in this axis, serving both the 2-pole and 4-pole armature windings.

Two-pole Circuits

The exciting field F_e, also called the 'control' or 'signal' field, forms the primary magnetic field, and the voltage generated thereby occurs only at the brushes A A. It has no ultimate effect on the 4-pole armature winding as the voltages generated in this are cancelled out.

Brushes A A are short-circuited and hence form with the two-pole armature winding a closed circuit producing a secondary magnetic axis at right angles to the primary magnetic axis, and therefore in the axis of brushes A A. The magnetic field produced by a current in this axis of the two-pole armature winding is able to generate a voltage between the brushes B B. Within the normal working range this voltage does not reach more than about ten per cent of the possible value.

The brushes B B are connected in series with a compensating winding F_cF_c and interpole coils I_2, which counteract, to a limited degree, the ampere-turns produced by the armature winding in the axis B B. The m.m.f. of windings F_e and F_c are thus in opposition to the m.m.f. of the armature windings in the axis B B.

This scheme therefore corresponds to the metadyne connections in which the degree of compensation provides for a limited amplification of the exciting energy at the brushes B B. This limitation is important in that the current in the short-circuited brushes A A is kept low and commutation

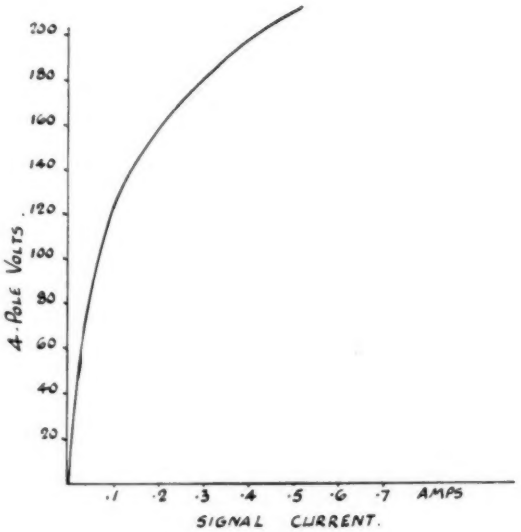


Fig. 3. Typical regulation curve for either 2-stage or 3-stage 'Magnavolt'

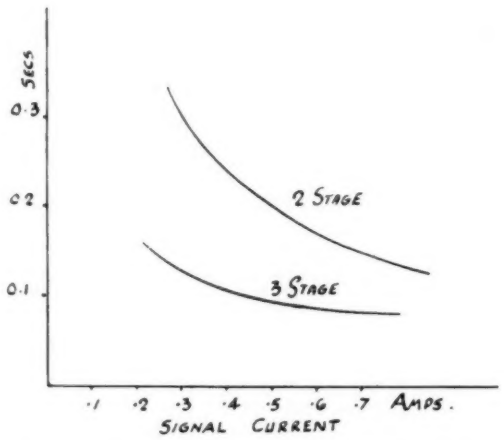


Fig. 4. Typical curves showing rate of response of 2-stage and 3-stage 'Magnavolt'

offers no problem. Thus the first-stage amplification is of a relatively low value; the rate of response, however, is correspondingly high.

Four-pole Circuits

The output from brushes B B is used for exciting the 4-pole field coils F_XF_X which are carried on the four mechanical poles of the machine. The coils

have a relatively small number of turns corresponding to the low voltage at the brushes B B.

The output is obtained from the 4-pole armature through brushes C C. Interpole coils I_4 which are provided on the common interpoles are connected in series with the 4-pole armature winding. The brushes C C are, of course, in contact with the commutator of the 4-pole winding; thus the 2- and 4-pole circuits are electrically entirely separate although sharing the same magnetic structure. This feature has the advantage that the 2-pole commutator and brushgear are always independent of the load conditions imposed on the output side, and the first two amplification stages are uninfluenced by the condition of the brushes and commutator of the 4-pole armature.

The commutating conditions of the output side are very favourable, being those of a simple 4-pole d.c. machine with interpoles. The three-stage amplifier is thus a very reliable machine under all operating conditions.

Amplification and Rate of Response

The power amplification in the first two stages may be up to 200 and a further amplification of 50 to 100 may be obtained in the third stage. The response obtained is very dependent on the degree of compensation provided in the 2-pole circuit. In this three-stage machine, power amplification comparable with the normal two-stage machine is achieved with a higher rate of response.

Comparison of Two- and Three-stage 'Magnavolt' Performance

For two-stage operation the machine is connected as shown in Fig. 2 with the brushes B B lifted off the commutator. The 'Magnavolt' in this simplified form has been extensively used and meets the majority of industrial requirements.

The voltage—signal current curve in Fig. 3 is a typical regulation curve of a 'Magnavolt', the same curve applying to a two- and three-stage machine but for quite different rates of response. The amplification at nominal output for the conditions shown in Fig. 3 is, for example, in the order of 5,000. The corresponding times for reaching 80% of the nominal output voltage are 0.09 seconds for the three-stage and 0.20 seconds for the two-stage connections.

In both cases the rate of response may be increased at the expense of the amplification ratio by inserting resistance in the 4-pole field circuit. Fig. 4 shows typical curves for the two- and three-stage machines, obtained by this method. This simple expedient is useful in certain applications.

A variation in the rate of response can be obtained in a three-stage machine by using a variable impedance in parallel with the compensating winding. This has the effect of varying the voltage at the brushes B B (Fig. 1) for a given control-field strength.

Insulation of Rotating Electrical Machinery

By E. JONES, B.Sc.(Eng.), M.I.E.E., A.M.I.Mech.E., A.M.Amer.I.E.E., Chief Insulation Engineer.

This article is in all essentials a reproduction of the paper presented by the author for the Symposium of Papers on Insulating Materials at the Institution of Electrical Engineers on the 18th of March 1953, and is published in this Journal by the courtesy of that Institution.

During the last 25 years or so there have been many papers [1-24] dealing wholly or partly with insulating materials and the insulation of electrical machines. This article is an attempt to bring up to date the information on new and improved materials which have become available during that period. It discusses their use in rotating machines, with the object of indicating the advantages obtained thereby and also the disadvantages and difficulties attendant with some of them. Practical experience over many years with some of these materials has revealed some serious drawbacks; on the other hand, others have proved to be even more useful than was thought at first.

It is becoming increasingly necessary to control material and manufacturing costs and it is most important that insulating materials be used economically, since the cost of the insulation in an electrical machine is usually a very significant proportion of the total cost. The properties of existing and of new materials must be studied in great detail, so that their applications may be chosen on a sound basis. It is sometimes found that a more expensive material is more economical than cheaper materials in actual production, owing to such factors as higher mechanical and electric strengths, superior resistance to electrical tracking, higher thermal conductivity and shorter processing times.

The insulation of large electrical machines, such as large a.c. generators for example, is a subject which requires unusual care, as the performance of the insulation during the expected life of the machine must be predictable with complete certainty. An insulation failure in a large generator can readily be a very expensive matter; hence the development of the insulation of such machines must be done in small stages, every change in material or processing method being thoroughly proved beforehand.

Changes in the insulation of small machines can usually be achieved much more quickly, as the insulation design is so very much less complex; it is in this field that the greatest advances have been made during the last 25 years.

The extensive Bibliography given at the end of this article is not intended to represent the sources used (except in the case of the most recent materials), but to indicate useful articles for further study.

GLASS FIBRES

Since the introduction of electrical glass fibres in about 1937, many changes have taken place in the design of the insulation of electrical machines, owing to the special characteristics of materials made from such fibres.

Woven Tapes and Cloths[6, 25-29]

Prior to 1937 the only textile material suitable for class-B machine insulation was woven from asbestos yarns, and the asbestos tapes available at that time suffered from a number of very serious drawbacks. For example, they were appreciably conducting, especially under damp conditions, owing to the presence of electrolytes; they were not very strong mechanically, and they could not be obtained thinner than 10 mils and even this only by heavy calendering, which meant that the tapes would 'swell' to about 12 mils during storage.

A further matter, of secondary importance, was that it was necessary to add about 15% of cotton to the yarn to facilitate weaving.

Glass tapes woven from continuous filament yarns are available in thicknesses from 3 to 11 mils. Even 3-mil woven-glass tape has an appreciably higher tensile strength than 10-mil woven-asbestos tape, as is shown in Table 1. Glass tape woven

Table 1

MECHANICAL AND ELECTRICAL TESTS ON GLASS AND ASBESTOS WOVEN TAPES

Minimum breaking load	*lb/in width*
3-mil woven glass	100
9-mil woven glass	250
10-mil woven asbestos	30
Insulation resistance of 1-*in length*	*megohms*
3-mil woven glass	∞
10-mil ordinary quality woven asbestos	0.08
10-mil electrical quality woven asbestos	60
10-mil electrical quality woven asbestos after 1 h at 95% relative humidity at 40° C.	37

Measured with a 500-volt Megger after normal conditioning, unless stated otherwise.

from substantially alkali-free glass yarn has a very much higher resistivity than the ordinary grade of woven-asbestos tape. Under damp conditions ordinary asbestos tape becomes decidedly conducting, whereas glass tape is not affected to any serious degree.

The higher tensile strength of glass tape made it possible to apply coil insulation much more tightly, with consequent improvement in coil ratings and insulation space factors. The very much higher resistivity of the glass tape eliminated many serious troubles which occurred with the ordinary grade of asbestos tape. Traction motors for 3-kV d.c. operation, for example, were very troublesome indeed when asbestos-taped armature coils were used, owing to the serious tracking which occurred during the high-voltage insulation test. Tracks up to 6 in long were frequently experienced, and only by very extended drying of the armatures followed by multiple dipping in varnish was it possible to produce armatures which would pass these tests. On replacement of the asbestos taping with glass taping the trouble ceased completely.

Glass taping has certain drawbacks. Armature or stator coils taped with glass are very susceptible to damage from abrasion, and it calls for no mean skill to wind a traction-motor armature, for example, without damaging the glass taping by abrasion against the edges of the slots. An armature wound without considerable care can look exceptionally untidy. Pre-treatment of the glass tape with an insulating varnish improves the resistance to abrasion to a marked degree, and the varnish treatment also reduces the tendency of the tapes to 'grinning'. In order to provide sufficient protection against abrasion to reduce the amount of care necessary in winding, the varnish build-up on the tape must be appreciable. Unfortunately this can reduce the flexibility and 'handle' of the tape.

Cloths woven from glass yarns[29] have proved useful for several applications. Cloth 2 mils thick can be used as a backing for mica[27, 28, 30] and very strong slot wrappers and mica tapes can be made. Glass-backed-mica slot wrappers for armature coils can be pulled up very tightly, thus reducing the risk of forming fins at the corners of the coil section during hot-pressing. Glass-backed-mica tapes make it possible to apply taped insulation very tightly, but are not suitable for taping around the corners of armature or field coils, owing to the lack of extensibility of the glass.

Comparatively little use is made of staple-filament glass textiles[29] for insulation purposes, probably because it is not yet possible to obtain staple cloths or tapes thinner than about 15 mils. Staple cloth thicker than 20 mils and treated in a suitable varnish has some use as a packing material for coil-support or winding-belt insulation in high-temperature armatures.

The resistance of glass textiles to heat ageing is well known, but the use of unvarnished textiles at temperatures higher than 150° C is a matter for some caution. The heating of glass textiles tends to remove the lubricant used in the manufacture of the textile, which then becomes very susceptible to damage by abrasion or vibration. This means that in some cases it is impossible to make use of the inherent heat-resistance of the glass.

Varnished Tapes and Cloths[6, 27-30]

In an attempt to provide a dielectric material based on glass textiles, varnished textiles were developed and have met with some success, although there is much room for improvement. Straight-cut varnished glass tapes have a high electric strength and can be applied fairly satisfactorily to straight conductors or to conductors having bends of large radii. However, they cannot satisfactorily be applied to conductors having bends of small radii, as the tape lacks sufficient elongation and it is

impossible to make it lie neatly. The same problem exists to a lesser extent with straight-cut varnished cotton tapes, but straight-cut varnished nylon tapes have appreciable elongation and can be applied very neatly.

The elongation of the varnished glass tapes can be much increased by cutting the tape on the bias. Bias-cut varnished glass tapes can be applied very neatly but have the disadvantage of being seriously damaged by 'pulling out'. If tension is applied to a bias-cut tape it is found that the electric strength drops rather rapidly to quite a low value as the load is increased, thus indicating rupture of the varnish film. The performances of various types of varnished tape are shown in Fig. 1. It will be seen that bias-cut varnished glass tape compares unfavourably with tapes having other bases.

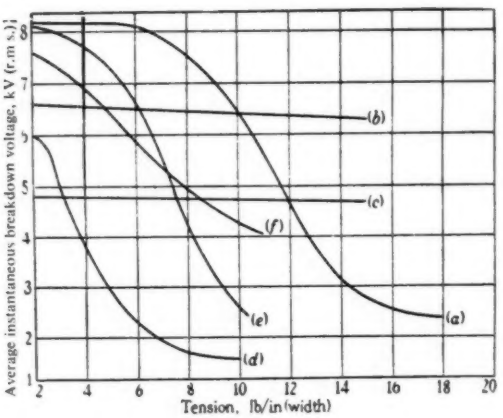


Fig. 1.—Effect of tension on the instantaneous electrical breakdown strength of varnished tapes

(a) 5-mil seamless bias-cut black varnished cotton tape.
(b) 6-mil straight-cut clear varnished glass tape.
(c) 3-mil straight-cut black varnished glass tape.
(d) 3-mil bias-cut clear varnished glass tape.
(e) 4-mil straight-cut yellow varnished Nylon tape.
(f) 4-mil bias-cut yellow varnished Terylene tape.

The tendency of bias-cut varnished glass tapes to pull out under tension can be reduced to some extent by using a comparatively hard varnish, but the varnished tape is then easily fractured by folding and creasing, which can occur accidentally during production; varnished cotton, silk and nylon will withstand this without harm, but hard-varnished glass is readily damaged.

Varnished glass tapes have been tried under production conditions for the taping of armature-coil conductors. The trials were performed with straight-cut material, but the results obtained were not encouraging. The conductors of experimental armature coils of the same design were insulated with 3-mil varnished glass in comparison with coils having mica-taped conductors. The mica tape contained one layer of mica splittings and the tape had a pressed thickness of 3·5 mils. All the tapes were applied half-overlapped. The experimental coils were tested between turns at voltages up to 1·25 kV (r.m.s.). In the case of the glass-insulated coils, 40 failures occurred in a total of 800 tests at a voltage of less than 1·25 kV, 12 of these failures occurring at less than 1 kV. Of 800 tests on mica-insulated coils, less than six failed below 1·25 kV, i.e. less than 0·7%.

The reason for the poor results obtained with the varnished glass insulation is considered to be mainly cracking of the varnish film, thus permitting failure due to the ingress of moisture. This can be overcome by drying the coils and subjecting them to special varnish treatment, but this introduces additional manufacturing costs. It is also suspected that thin varnished glass tapes are very sensitive to damage by small particles of copper or other foreign matter. Under production conditions it is extremely difficult to ensure absolute cleanliness of the copper, and even the smallest amount of copper dust on the conductors appears to increase the chances of inter-turn failure. Mica tape is much more tolerant of minute foreign particles. Much better results were obtained with 5-mil varnished glass tape, but the additional tape thickness, as compared with the 3·5-mil mica tape, is not attractive to machine designers.

Petterson[30] has mentioned the use of polyester varnished glass tapes for insulating the armature conductors of traction motors. It may be that this type of varnish has a tendency to be self-healing if the varnish film cracks during the taping operation.

Sleevings and Cordage[29]

Braided-glass sleevings fulfil a useful function for such applications as the insulation of commutator, stator-coil and solenoid-coil leads. Such sleevings are particularly useful when adjacent to soldered or brazed joints, as the glass is not seriously affected by the heat. Varnishing of the sleeving is

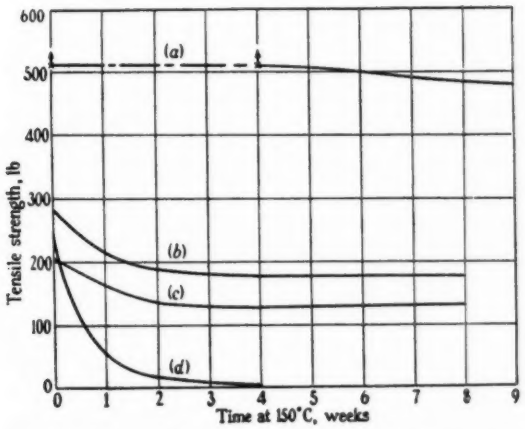


Fig. 2.—Effect of temperature on the tensile strength of $\frac{1}{8}$-in diameter cords

(a) Glass twisted cord.
(b) Terylene twisted cord.
(c) Terylene braided tubular filled with Terylene yarns.
(d) Hemp whipcord.

particularly effective in preventing fraying, and suitable varnishing can improve the electrical breakdown of the sleeving sufficiently to make it suitable for low-voltage duty (up to 440 volts a.c.). Sleevings varnished with silico-organic varnish are useful even for service operation at normal temperatures. Glass sleevings varnished with normal cloth varnishes can become brittle during the varnishing processes applied to motor windings, for example, whereas silico-organic varnishes harden very much more slowly than orthodox oil varnishes and do not normally become brittle.

Glass-fibre cords and twine are very strong in tension and they retain their tensile strength at high temperatures (as shown in Fig. 2) and under damp, tropical conditions. Such cords are, however, difficult to secure, as knotting reduces the tensile strength by at least 70%. If the cording is applied in 'cricket bat handle' fashion the results can be quite satisfactory. Pre-treatment of the cord with varnish facilitates tying and improves the abrasion resistance of the cord. Braided-glass sleevings are sometimes preferred to twisted cords for the binding of windings[31] or commutator V-rings, as the sleevings will lie flat and give a smoother finish. One serious disadvantage of glass cords is that they have a very low elongation and when used for binding non-resilient components the binding is apt to be either tight or slack; there are no degrees of tightness as can be obtained with hemp, nylon, or Terylene cords.

Laminates[32-40]

By using special production technique, successful laminated glass-cloth boards can be made, using either a phenolic or a melamine resin bond. Such laminates are very strong mechanically, but their electrical properties are indifferent. Phenolic-resin-bonded glass laminates have found some use for armature slot-wedges and turbo-alternator rotor-endwinding packings, where maximum strength and good heat resistance are required.

Melamine-resin-bonded laminates are used extensively in America and to a lesser extent in Britain. The advantages of this type of laminate are its phenomenal resistance to electrical tracking and the fact that under the effect of an electric power arc poisonous fumes are not generated to any significant extent.

Glass laminates bonded with silico-organic resin have very interesting properties. Their mechanical strength is adequate and their resistance to heat ageing is much superior to laminates bonded with other resins. Such laminates are used to a limited extent for slot wedges in machines which have to operate continuously at temperatures in excess of 150° C.

Table 2 gives average properties for various glass laminates. It will be noted that the water absorption of melamine-resin-bonded glass laminates is rather high; this material is not normally suitable for use under damp conditions. So far as electrical properties and moisture absorption are concerned, neither the melamine- nor the phenolic-resin-bonded glass laminates can be considered as any improvement on a general-purpose phenolic-resin-bonded cotton-fabric laminate, but the silicone-glass laminates are rather more promising in these respects.

Glass laminates bonded with polyester resins have found considerable application in the aircraft industry, owing to their high strength and their ability to be formed into complex shapes using contact resins. Little use is made of contact-resin laminates in electrical machines, although they may prove useful in this field in the future as it might be expected that the electrical properties of such laminates would be superior to those of phenolic-, melamine- or silico-organic-bonded laminates.

Table 2

MECHANICAL AND ELECTRICAL PROPERTIES OF BONDED GLASS-FIBRE LAMINATED BOARDS

Bonding resin	Tensile strength	Compression strength	Cross-breaking strength	Impact strength (notched Izod)	Electric strength at room temperature		Water absorption in 24 hours	
					Short-time test $\frac{1}{8}$ in thick	Step-by-step one-minute test $\frac{1}{8}$ in thick	$\frac{1}{8}$ in thick	$\frac{1}{2}$ in thick
	lb/in² × 10³	lb/in² × 10³	lb/in² × 10³	ft-lb/in	volts/mil	volts/mil	%	%
Melamine	20–25	70–80	25–30	20–30	150–200	100–150	1·0–1·5	0·8–1·0
Phenol	20–25	45–50	20–25	8–10	150–200	—	0·3–0·5	—
Silicone	14–16	35–40	15–25	10–15	250–300	—	0·5–0·7	0·3–0·4

The machining of glass laminates is not unduly difficult and they are somewhat less difficult to machine than asbestos laminates; this may be due to the higher thermal conductivity of the glass laminates.

Wire Coverings[29, 41]

Glass 'silk' wire coverings were mentioned as long ago as 1926, but it was not until 1938 that glass-textile wire coverings were available in a practical form, as lapped glass and braided glass. For many purposes a single-lapped covering is not favoured, as it is not usually sufficiently robust to withstand winding operations, but provided that adequate care is taken, the single-lapped covering can give good results. The overall covering thickness on round wires is 3-5 mils, which gives the covering a decided advantage as compared with asbestos coverings.

Double-glass-lapped wire and strip is extensively used for winding all types of electrical machines, including random-wound a.c. stators, wire-wound d.c. armatures, and field coils. The covering has a total thickness of 6-8 mils on round wires and 10-14 mils on strips. Nominally the covering thickness is little different from that of asbestos coverings, but the great advantage of glass coverings lies in the consistency of the covered dimensions. This means that the space factor of windings of glass-covered wires or strips is appreciably higher than that of the same windings with asbestos-covered conductors.

Braided glass coverings are generally superior to lapped coverings on rectangular conductors which have to be bent on edge, such as occurs when forming armature coils, since the braided covering is better able to withstand such bends without opening up. Braided coverings are usually thicker (12-14 mils on round wires and 14-16 mils on strips) than double-lapped coverings and are more expensive.

Great care has to be taken in the varnishing of glass coverings. Unvarnished coverings are, of course, almost impossible to handle. If the covering is varnished to such an extent that a smooth shiny surface is obtained, its resistance to abrasion is a maximum and such a finish is suitable for winding random-wound stators. The use of a heavy varnish film increases the covering thickness by about 1 mil. In the winding of shunt-field or solenoid coils the covering is not subjected to such serious abrasion and it is not necessary to have such a heavy varnish finish; in fact, it is an advantage during winding if the covering has a matt surface, as this reduces the tendency of the wire to slip.

Glass-fibre Paper

Papers which contain at least 70% of glass fibres have been produced in this country and some interesting synthetic-resin-bonded laminates have been made from such papers. Phenolic laminates with cross breaking strengths up to 15,000 lb/in² have been produced. Papers composed entirely of glass fibres have been produced experimentally in America,[42] but the published information indicates that they are being considered for capacitor insulation and nothing has yet been reported about other applications.

A bonded laminate containing a base of 100% glass-fibre paper would appear to have many uses. It would be expected that such a laminate would be much cheaper than the usual glass-fabric laminate

and its dielectric properties may well be superior to the fabric laminate.

The glass-fibre paper which has been made in Britain contains an appreciable amount of cellulose material, so that the organic content of, for example, a phenolic laminate with a base of this material would be rather high. The glass-fibre-paper content of such a laminate is not greater than 60% and only 70% of this paper is glass. This influences the heat-ageing properties of the material at elevated temperatures, as is shown in Fig. 3.

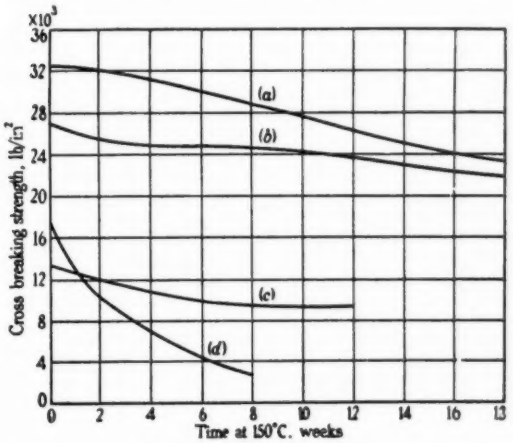


Fig. 3.—Effect of temperature on the cross breaking strength of various laminated boards; tests in accordance with B.S.972, using material 5/32 in thick

(a) *Phenolic bonded asbestos-felt board.*
(b) *Phenolic laminated asbestos-paper board.*
(c) *Phenolic laminated glass-fibre-paper board.*
(d) *Phenolic laminated cotton-fabric board.*

Melamine-resin-bonded glass-fibre paper might prove to be attractive if it can be manufactured more cheaply than melamine-resin-bonded glass-fabric laminate, which is interesting because of its phenomenal resistance to tracking but restricted in use by its high cost.

ASBESTOS FIBRES

Any discussion on the use of asbestos textiles in the insulation of electrical machines must inevitably contain some comparison with glass textiles. Both these materials are extremely valuable to the insulation engineer and each has its place in insulation designs.

Woven Tapes and Cloths[43]

The difficulties experienced with the asbestos tapes which were available prior to 1940 are mentioned under this sub-heading on page 160.

The use of electrical glass tape eliminated the leakage troubles, but glass textiles brought other problems, such as the difficulty of producing satisfactory Bakelized slot sections on traction armature coils. A Bakelized asbestos-tape finish on an armature-coil slot portion is very robust mechanically. A Bakelized glass-tape finish is much more sensitive to abrasion during winding, and other methods of 'blocking' the slot portions had to be developed which were still not so robust as the Bakelized asbestos finish.

In 1940 an improved type of asbestos tape was produced which was made from specially selected and specially treated asbestos. These tapes have a very much better electrical performance than the old type of asbestos tapes (see Table 1). The improved asbestos tape has the robustness and abrasion resistance of the old type of tape, although the tensile strength is somewhat lower. The electrical properties of the improved tape are sufficiently good to permit its use in 3,000-volt d.c. windings, although it is probable that many manufacturers would still prefer to use glass textiles for such machines.

The tensile strength of the improved asbestos tape is much lower than that of glass tape of the same thickness (see Table 1), but the asbestos tape has appreciably greater stretch and consequently its lower tensile strength does not usually present a serious problem.

It is perhaps unfortunate that asbestos tapes are not available in a thickness of 5-6 mils. If it were possible to produce a 5-6 mil asbestos tape with a tensile strength of not less than that of the present 10-mil asbestos tape, it is probable that an appreciable amount of the 5-mil glass tape at present used would be replaced by asbestos tape.

Asbestos tapes contain up to 15% by weight of cotton fibres, which is necessary to increase the yarn strength. It would not appear unreasonable to replace this cotton by glass fibres,[44, 45] which would undoubtedly improve the tensile strength of the tape and eliminate the present rather high organic content. Alternatively, it might be interesting to use Terylene or nylon fibres in place of the cotton. Mixed textiles have been produced,

but these have mainly been made by replacing either the weft or the warp threads by some material other than asbestos. Such mixed weaves have their uses, but much remains to be done.

Sleevings and Cordage

Asbestos sleevings are little used in rotating machines, as the minimum wall thickness available is about 30 mils, which is much too great for many purposes. Furthermore, the electrical properties of such sleevings are comparatively poor. One interesting application of asbestos sleevings is the insulation of conductor subdivisions in transposed conductors for high-voltage large a.c. machines.[43] In this application the electrical characteristics of the sleeving are relatively unimportant. Asbestos sleevings are, of course, used extensively as a wire covering in domestic appliances.

Asbestos cords and ropes have a certain use in machines, mainly for packing and filling. When saturated with synthetic-resin varnish or with polyester resins, very robust packings and fillings can be achieved.

Laminates

Synthetic-resin-bonded asbestos woven cloth is of interest mainly because of its mechanical ruggedness and its resistance to heat. Laminates incorporating coarse cloth (cloth thickness approximately 30 mils) have very poor electrical properties and they can be considered as insulating materials only at very low voltages and electric stresses of less than about one volt per mil. These coarse laminates have high tensile, compression and impact strengths, and are also very resistant to abrasion. Such materials are useful where mechanical strength at high temperatures (up to 150° C) is required, such as, for example, end-winding packing blocks in turbo-alternator rotor windings.[19,24] Laminates of this type are also sometimes used for armature slot wedges.

The electrical properties of synthetic-resin-bonded laminates of fine asbestos cloth (cloth thickness approximately 15 mils) are superior to those of coarse cloth laminates. Fine cloth laminates can under certain conditions be stressed continuously at up to 40 volts/mil for laminate thicknesses of $\frac{1}{8}$ in or less. Fine laminates do not seem to be used very widely, probably because of their comparatively high cost and scarcity. Mention has been made[20] of the use of Bakelized asbestos cloth troughs for turbo-alternator rotors.

Asbestos-cloth laminates bonded with melamine resins have found a certain amount of use, particularly in America; such a material has almost no proneness to track, and this is a most useful characteristic under damp or dirty conditions.

Synthetic-resin-bonded asbestos-paper laminates are of considerable value when a heat-resisting material of reasonable dielectric properties is required. The mechanical strength of these laminates is good and the dielectric properties are almost comparable with those of laminated cellulose-paper boards to B.S.1137: 1949, type 3. Asbestos-paper laminates can be used for switchboard panels, terminal boards and packing blocks in machine windings. In common with other types of asbestos laminate, the asbestos-paper laminate has a much higher thermal conductivity than many other such materials. Melamine-resin-bonded asbestos-paper laminates have recently made their appearance in Britain. Such materials should have considerable use where a non-tracking heat-resisting board of reasonable electric strength is needed. The use of asbestos-paper laminates for slot wedges is not completely successful, as the material has a tendency to chip at the edges whilst the wedges are being driven into position. If the wedges can be inserted satisfactorily they can be successful under service conditions.

Resinated asbestos felt or fleece is not a laminate in the usual sense. The individual sheets of felt are not usually thinner than $\frac{1}{16}$ in. By stacking the appropriate number of felts and curing under heat and pressure an immensely strong board can be produced. A fully cured and pressed asbestos-felt board is undoubtedly the strongest board material made from asbestos. Cured resinated-asbestos-felt board may be used for wedges in machines operating at high temperatures. The performance of the material at 150° C in comparison with other laminates is shown in Fig. 3. The dielectric properties of cured resinated-felt board are very poor; indeed, the material is best considered as a non-insulator.

Table 3 gives the mechanical and electrical properties of typical asbestos laminates at room temperature.

Table 3

MECHANICAL AND ELECTRICAL PROPERTIES OF BONDED ASBESTOS FABRIC AND PAPER BOARDS

Material	Tensile strength	Compression strength	Cross breaking strength	Impact strength (notched Izod)	Electric strength at room temperature		Water absorption in 24 hours
					Short-time test	Step-by-step one-minute test	
	lb/in² × 10³	lb/in² × 10³	lb/in² × 10³	ft-lb/in	volts/mil	volts/mil	%
Phenolic-bonded asbestos-cloth board (coarse cloth)	10–12	38–40	18–20	—	Very low	—	—
Phenolic-bonded asbestos-cloth board (fine cloth)	8–9	35–38	16–18	—	100–120	< 60	—
Phenolic-bonded asbestos-paper board..	13–15	35–38	20–22	1·6–1·8	150–200	100–120	0·3–0·5
Melamine-bonded asbestos-paper board	13–15	35–38	30–35	1·2–1·8	150–200	100–120	0·4–0·6
Phenolic-bonded asbestos-felt board ..	19–22	78–80	21–25	5·0–6·0	Very low	—	—

Wire Coverings[41]

Asbestos coverings for wire and strip are used to a considerable extent in machines, although glass coverings are a serious challenge. Glass coverings are more consistent in thickness and can be obtained much thinner than asbestos coverings; this is illustrated in Fig. 4. Nevertheless, asbestos coverings are favoured in many cases, because of their greater resilience and abrasion resistance. In random windings, e.g. mush-wound stators for industrial motors, it is probable that a specially varnished glass-covered wire is superior. In a random winding crossed wires can occur, resulting in areas of high local pressure. Specially varnished glass coverings will withstand these high local pressures, whereas asbestos coverings can be penetrated or torn. For regular windings asbestos coverings are entirely satisfactory, except that the space factor is generally inferior to that of a winding of glass-covered conductors.

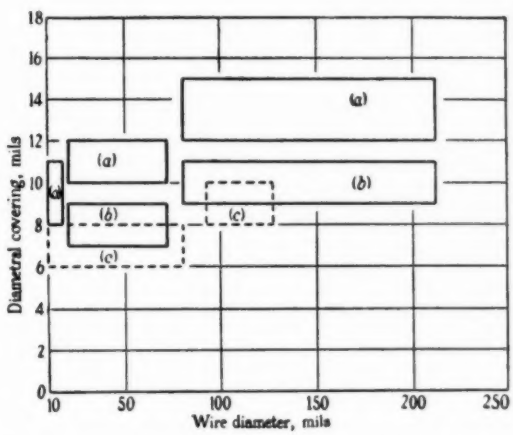


Fig. 4.—Covering thicknesses of asbestos and glass insulated round wires

(a) Ordinary asbestos covering to B.S. 1497.
(b) Fine asbestos covering.
(c) Double glass-lapped covering.

It is understood that some attention is being given to the idea of applying asbestos in the form of paper to conductors, the paper being the high-purity material developed in the United States during recent years. Very little information is at present available on asbestos-paper-covered conductors, but it would be expected that a covering of this type would have a higher electric strength than the felted coverings.

Papers

Some years ago a range of high-purity asbestos papers[47, 48] was introduced which opened up new possibilities in high-temperature dielectrics. Mention has been made of the use of these new papers in air-cooled transformers, but little has been said about their use in the insulation of rotating machines.

A type of high-purity asbestos paper is now available which is reinforced with glass fibres, and this material would appear to have possible applications in machines, as its tensile strength and resistance to tearing are quite high. The unreinforced asbestos paper is very difficult to handle as it is very weak mechanically, but when combined with glass it is much more interesting. When reinforced with glass and treated in a suitable insulating varnish, the asbestos paper has quite a high short-time electric strength and can replace mica in certain cases. Its long-time electric strength, however, is not high, and in this respect it is very much inferior to mica.

Specially treated asbestos papers have been suggested for commutator separators[49] and small commutator V-rings.[49] The use of a polyester impregnant for the asbestos paper has been mentioned.

Ordinary qualities of asbestos paper treated with a suitable resin or with vulcanized rubber are used to an appreciable extent in machines, particularly for the insulation between the turns of strip-wound field coils for salient-pole alternators,[23] traction motors, etc. There is no obvious need for the much more expensive high-purity asbestos papers for such applications. Ordinary asbestos papers in combination with glass and suitable varnish treatments have useful dielectric properties, but superior results are obtained by using high-purity asbestos paper. It has to be borne in mind, however, that the high-purity papers are at present at least 20 times more expensive than ordinary papers.

COTTON FIBRES

The most important development which has taken place in the field of cotton tapes and cloths in the last 20 years has been the development of esterified or acetylated cotton.[50]

Acetylated-cotton Tapes

Tapes woven from acetylated cotton[51] have a remarkable resistance to heat tendering, as is indicated in Fig. 5, where the performance of the acetylated tapes is compared with that of ordinary dynamo cotton tapes. From the results obtained it would not be unreasonable to consider the acetylated tapes as suitable for class-B industrial machines, although this would not be in accordance with the existing British Standard classification of insulating materials. It would be quite permissible, however, to use acetylated-cotton tapes in class-A machines subjected to overloads of short duration.

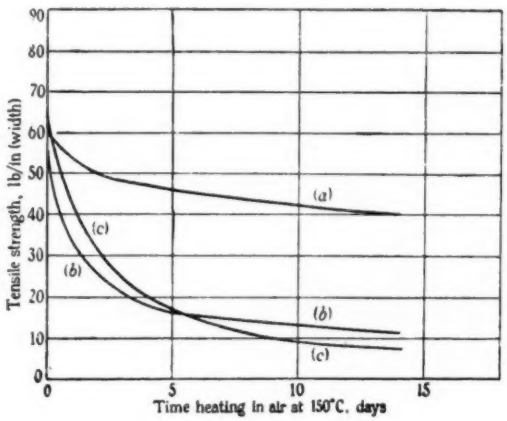


Fig. 5.—Effect of temperature on the tensile strength of acetylated and normal cotton tapes

(a) 13-mil acetylated cotton tape (acetyl content approximately 30%).
(b) 6-mil Egyptian-cotton tape.
(c) 8-mil American-cotton tape.

Another advantage of acetylated cotton is its superiority under damp conditions[52] as compared with ordinary cotton. It is also claimed that the material is highly resistant to micro-biological decay.[53,54] In the insulation of electrical machines it is most unusual to use cotton in an untreated condition. Normal varnish treatment greatly reduces the moisture pick-up of cotton textiles, although multiple varnish treatment is sometimes necessary when very damp tropical conditions are likely to arise. Acetylated cotton would appear to offer distinct advantages under severe service conditions.

The acetylation of cotton is rather expensive and to raise the acetyl content of tapes to approximately 30% increases the cost of the tape by as much as 50%.

POLYAMIDE MATERIALS

Nylon has not been used very extensively in machines, owing to supply difficulties and cost, but the material offers a number of technical

advantages which, in some cases, outweigh the higher cost.

Varnished Nylon Woven Tapes and Cloths

Nylon textiles have appreciable elasticity and in many cases it is possible to use a straight-cut varnished nylon tape in place of bias-cut varnished silk or cotton. The elasticity of the nylon gives adequate stretch to enable neat and tight taping to be achieved on irregular shapes such as armature coils. Straight-cut varnished tapes are, of course, cheaper than bias-cut—especially seamless bias-cut—tapes and this means, for example, that a 5-mil straight-cut varnished nylon tape is cheaper than 5-mil seamless bias-cut varnished pure silk.

Straight-cut varnished nylon tapes are very strong mechanically and their dielectric properties are good, as is shown in Fig. 1. It is not unreasonable to replace, for example, a 7-mil seamless bias-cut varnished cotton tape with a 5-mil straight-cut varnished nylon tape and thus effect a saving in both cost of material and insulation thickness.

The performance of straight-cut varnished nylon tapes in comparison with other varnished tapes is illustrated in Fig. 1.

Synthetic-Resin-Bonded Nylon-cloth Laminates

Phenolic-resin-bonded nylon-cloth laminates have some interesting properties. In thicknesses up to $\frac{1}{8}$ in they are particularly satisfactory for punching into small accurate shapes, especially if the material is punched hot. It is probable that these laminates can be punched more cleanly than any other type.

The performance of nylon laminates under heat ageing is good. It appears that there is some interaction between the phenolic resin and the nylon which results in what appears to be a plasticizing of the phenolic resin. On heat ageing at 120-150° C the laminate becomes more pliable and the ageing has to be carried on for a long time before embrittlement takes place.

These special properties of nylon laminates make the material useful for small packing pieces or other small pieces for use in coil construction which are required to be made accurately. The present price of nylon laminates is high and this severely limits the use of the material.

The mechanical and electrical properties of phenolic-resin-bonded nylon laminates are given in Table 4.

Table 4

MECHANICAL AND ELECTRICAL PROPERTIES OF PHENOLIC-RESIN-BONDED LAMINATED NYLON-CLOTH BOARD

Tensile strength	7,000–10,000 lb/in²
Compression strength	35,000–40,000 lb/in²
Cross breaking strength	14,000–20,000 lb/in²
Impact strength, notched Izod test	11–13 ft-lb/in
Short-time electric strength at room temperature	300–350 volts/mil
Step-by-step electric strength at room temperature	200–250 volts/mil

Nylon Film

Nylon film has a high tensile strength (of the order of 10,000 lb/in²) and a high tear strength. Such film is used in America as a slot liner and inter-phase insulation in small motors, apparently without any additional mechanical reinforcement. The use of plastics films as slot liners in small motors is attractive from cost considerations, but plastics films in general have a low tear resistance and it has been found necessary to reinforce the slot liner by using pressboard or vulcanized fibre. Nylon film is one of the few plastics films with a high tear resistance and an adequate resistance to high temperature; it is claimed that it will withstand continued exposure to a temperature of 120° C. Nylon film 5 mils thick is produced on a very small scale in Britain, but greater thicknesses are not yet available.

TEREPHTHALIC POLYESTER MATERIALS

The development of polymers of ethylene glycol terephthalate[55] (Terylene) has been followed with much interest, as textiles produced from this material have some outstanding properties, notably resistance to high temperatures. It is probable that Terylene offers a serious challenge to glass and asbestos textiles for electrical insulation.

Terylene Woven Tapes and Cloths

Woven-Terylene tapes are of especial interest, because of their high tensile strength, tear resistance and resistance to high temperatures. Fig. 6 illustrates the performance of typical tapes in

comparison with glass woven-tapes. It may be concluded from the results at high temperatures that Terylene tapes are suitable for class-B machines. Unfortunately, since Terylene is organic it cannot be considered as conforming to the existing British Standard definition of class-B insulation, but it is to be hoped that the Standard will be modified so as to permit insulation engineers to use Terylene and other high-temperature organic materials at their discretion.

It is understood that Terylene is highly resistant to microbiological attack, so that it should be suitable for machines which have to operate under damp tropical conditions.

At present the thinnest Terylene cloth available has a thickness of 2·8 mils. Cloth thinner than 2 mils has been produced experimentally by caustic-soda treatment of the 2·8 mil material and may prove to be useful as a backing for mica tapes in place of silk or glass, although the present high price of the Terylene is a deterrent.

Varnished Terylene Woven Tapes and Cloths

Terylene cloth varnished with a suitable varnish can be cut into either straight-cut or bias-cut tapes which have the advantage of high mechanical strength, good resistance to heat and fairly high electric strength. Were it not for the present wording of the British Standard classification of class-B insulation, it would not be unreasonable to use varnished Terylene cloth or tape in Class-B machines such as industrial motors and perhaps traction motors.

As a dielectric material, varnished Terylene is much more attractive than varnished glass, as the varnish film is much less readily damaged when a Terylene base is used. Terylene has appreciable elasticity and it may be possible to use straight-cut varnished Terylene as it may have sufficient stretch to permit neat taping without recourse to bias-cut material. The dielectric performance of varnished Terylene tape in comparison with other varnished textiles is illustrated in Fig. 1. Varnished Terylene tapes have been subjected to ageing tests at 150° C, and even after 1,000 hours the tape may be folded and creased without any sign of cracking, whereas varnished glass tapes crack very readily after such a test.

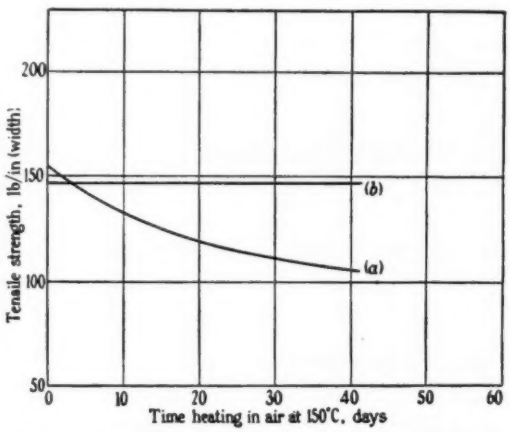


Fig. 6.—Effect of temperature on the tensile strength of Terylene and glass tapes

(a) 5-mil Terylene tape, heat-sealed edges.
(b) 5-mil glass woven tape (electrical quality glass).

Terylene Cordage

Cords made from Terylene yarns are of very high strength although not as strong in tension as glass cords. The loss of strength of Terylene cords due to ageing in air at 150° C is shown in Fig. 2, compared with glass cords of the same nominal diameter. Terylene cords are, however, much easier to use than glass cords, as the Terylene has sufficient elasticity to enable lashing to retain its tightness. Furthermore, Terylene cords do not cut the skin as do glass cords. Terylene cords are very suitable for lashing machine windings. The ends may be fastened by knotting, whereas glass cords suffer very severely due to knotting; knotting reduces the tensile strength of glass cords by at least 70% whereas the tensile strength of Terylene cords is reduced by only 20%.

Two main types of Terylene cord are being manufactured. One is in the form of a tubular braid filled with yarn and the other is the normal twisted cord. The filled braid lies flatter and more neatly and has less tendency to unravel at the ends.

Terylene Film

Terylene film known as 'Mylar'[56] has been made in the United States, although it is being considered mainly as a capacitor dielectric.[57] The film is very strong mechanically both in tension and tearing.

This material may well find extensive use in machines. The film has a fairly high electric strength and it is understood that its voltage endurance is good. From the limited amount of information available on this material it would appear to have a tremendous future, although it seems unlikely that it will be available in quantity for several years.

The tensile strength of Mylar at 25° C is stated to be 25,000 lb/in² compared with 2,400 lb/in² for polythene and 1,100 lb/in² for cellulose acetate. Mylar films as thin as 0·00025 in have been produced. It is claimed that Mylar retains most of its mechanical properties at temperatures from −51° C to 160° C, and that even after 1,000 hours at 160° C the mechanical strength is still remarkably high. Mylar requires no plasticizer—hence it has high dimensional stability. The short-time electric strength of films thinner than 0·001 in is claimed to be higher than 4,000 volts/mil.

SYNTHETIC-RESIN WIRE ENAMELS

The advent of synthetic-resin-enamelled round wires some 12 years ago initiated many changes in the manufacture of rotating machines, particularly small industrial motors. Prior to the development of these synthetic resin enamels many attempts had been made to use oleo-resinous enamelled wires, but wire of this type was so susceptible to damage by abrasion and solvents that few manufacturers persevered with it. The synthetic enamels represented a very considerable advance, and manufacturers were not slow to take advantage of their greatly improved abrasion and solvent resistance. It is probably true to state that, to-day, most manufacturers of rotating machines use synthetic-resin-enamelled wires.

Vinyl-acetal-enamelled Wires[58]

Vinyl-acetal wire enamels were developed in the United States in 1938[59] and the application of this enamel was commenced in Britain in 1940. The wire proved to be particularly suitable for such applications as random-wound stators for small industrial[60] and fractional-horse-power motors. The enamel is sufficiently robust to withstand abrasion during winding; in fact, it withstands abrasion better than any of the textile-covered wires or paper-covered enamelled wire. The finish of the vinyl acetal enamel is very smooth and this greatly facilitates the insertion of random-wound coils into semi-closed slots, as the wire can almost be 'poured' into the slots. The use of the new enamelled wire makes possible a considerable reduction in winding times and also a marked reduction in the length of the mean turn.

The solvent resistance of vinyl acetal enamels is high and this makes it possible to use synthetic-resin coil varnishes having aromatic solvents for the treatment of windings, with a resultant improvement in the moisture resistance, thermal dissipation and mechanical rigidity of the windings.

The use of vinyl-acetal-enamelled wires for wound rotors and armatures needs careful consideration of the varnish treatment process. Although the wire enamel is highly resistant to aromatic solvents, it is softened to a slight extent by them, and it is necessary to ensure that no solvents remain entrapped in the windings after varnish treatment. As the winding is heated in service, inter-turn faults can develop under the action of centrifugal forces in places where solvents still remain. Where the complete removal of solvents from the rotor or armature windings is impracticable, the use of varnishes containing aromatic solvents is not to be recommended.

Vinyl acetal enamel is, of course, a class-A material, although it is known that some class-B industrial machines have been wound with such wire and have apparently given good service. There is no doubt that vinyl acetal enamel can be rated higher than class A, i.e. 105° C. The introduction of a new class with a temperature limit of 120° C has been proposed and it is considered that vinyl acetal enamels would be quite satisfactory at such a temperature.

Vinyl acetal enamels are used in traction-machine armatures and field coils to some extent, particularly in auxiliary machines.[61] Such wires are also used in small machines for aircraft use, where intermittent temperatures up to 150° C or more are possible. This seems perfectly reasonable, as these machines are not usually required to have a long life. Even at 200° C the useful life of vinyl acetal enamels is greater than 100 hours.[62, 63] With suitable varnish treatment the life at 200° C can be extended to several hundred hours.

Vinyl-acetal-enamelled wires are used very extensively for the winding of stators for hermetically sealed domestic refrigerator units [64-66] which use refrigerants of the Freon type. The

windings of such stators are not varnish treated, so that the enamelled wire is directly exposed to the refrigerant.

Polyamide-enamelled Wires

Wires enamelled with nylon enamel made their appearance in this country in about 1939, and in many respects are comparable with vinyl-acetal-enamelled wires. One marked difference is that the nylon enamel does not adhere to the wire as firmly as vinyl acetal enamel and there is a risk of retraction of the enamel from a nick unless special care is taken in the formulation and the application. Large quantities of nylon-enamelled wire were used in this country during the war and the results were entirely satisfactory. In the last five years or so, nylon-enamelled wire has lost its popularity in this country, but it is not clear why this should have happened; this class of wire is still extensively used on the Continent.

Nylon enamel has a greater resistance to aromatic solvents than vinyl acetal enamel, and an interesting recent development is a combined covering consisting of vinyl acetal enamel with an outer layer of nylon enamel. It is claimed that this combination has the good features of both enamels. It is believed that the nylon enamel adheres very satisfactory to the vinyl acetal enamel.

Ethoxyline or Epoxide Wire Enamels

Wire enamels based on ethoxyline or epoxide resins have been produced during the last few years. Such enamels are as robust as the vinyl acetal enamels and their dielectric properties are of a high order. One distinct advantage of these enamels is their superior resistance to heat. Wires enamelled with ethoxyline resins have been subjected to 200° C for more than 500 hours with most interesting results. It would appear that these enamels may well have a very appreciable life at 150° C. Enamels of this type may well be considered as suitable for class-B traction ratings in the future.

The ethoxyline or epoxide enamels can be applied in the enamel thicknesses laid down in B.S.1844: 1952.[58]

SYNTHETIC-RESIN COIL VARNISHES[67, 68]

The oil-modified synthetic-resin varnishes which became available in 1938 proved to be of considerable value, owing to their superior bonding characteristics, through-hardening properties and moisture resistance. Motor windings treated with such varnishes are in many cases sufficiently well bonded to make it unnecessary to use any additional bracing of the windings. The curing time needed with varnishes of this type is usually appreciably less than is required with the ordinary oleo-resinous varnishes, although higher curing temperatures are necessary. In some cases the higher curing temperatures are an embarrassment, owing to tendering of any organic textile materials used in the winding.

An interesting development of the technique of using synthetic-resin varnishes was the cold-dip process. This process is normally used with windings of vinyl-acetal-enamelled wire, although it may also be used with windings of glass-covered wires. The wound machine is dipped cold in cold varnish and after a suitable draining period the wound machine is stoved at a temperature of 170–180° C. The high temperature of stoving relieves any stresses in the wire enamel and seals any cracks which may have formed in it, whilst curing of the dipping varnish takes place very rapidly. Windings treated in this way have a remarkably good performance under damp tropical conditions and are often more satisfactory than hot-dipped or vacuum-impregnated windings when judged on the performance of the winding under tropical conditions. The cold-dipping process is not considered reliable for the treatment of cotton-covered windings, as these may contain a considerable quantity of moisture.

Varnishes for cold-dipping usually contain a xylol solvent. During the stoving of the dipped winding an azeotropic reaction takes place and moisture from the undried winding comes off with the xylol.

POLYESTERS AND ETHOXYLINE (EPOXIDE) RESINS

Polyester resins for the bonding of glass fabrics have been used in the aircraft industry for several years for the manufacture of radomes and various structural parts, but during the last two years the electrical industry has taken a great interest in such materials and also in the ethoxyline resins which can be applied in a somewhat similar way.

Casting and Impregnating

The use of polyester or ethoxyline casting resins for impregnating and potting transformers[69] is now a comparatively well-known practice, but this technique has also been applied to the windings of electrical machines.[70] These resins are, in effect, solventless in that the solvent (usually styrene, but occasionally divinyl benzene) is completely reactable with the resin. Certain formulations of the resins have remarkable penetration power, even into deep tight windings. The resins may be cured at room temperature or at an elevated temperature, depending on the catalyst used. The degree of 'fill' which can be obtained with polyester or ethoxyline resins is almost complete, and this is obtained much more readily than is the case with orthodox solventless varnishes.

It may be that resins of these types will replace solvent-type varnishes completely in the future, although two main difficulties have yet to be overcome; one is that the polyester resins have to be catalyzed, thus entailing a short pot life, and the other is the comparatively high cost of the resins. Certain catalysts are available which in conjunction with refrigerated storage will not shorten the pot life too seriously, and it has been found possible to store certain formulations for many months without undue setting-up. Some of the ethoxyline formations can be set by heat alone, but this introduces other production difficulties, owing to the high temperature required (up to 180° C) to obtain the most satisfactory results.

Laminating

Contact laminates bonded with polyester resins have not found extensive use in machines, owing mainly to their comparatively high cost. In some cases specially shaped laminates have been used. One example is a polyester-bonded glass laminate formed into a U-shape for inter-coil separation in class-B random-wound stators for small induction motors.

Polyester-bonded laminates are very useful where small numbers of specially shaped laminates are required and where the use of high-pressure laminates would be uneconomical because of the high tool costs.

MICA BONDS

Little change has been made in the choice of mica bonds during the last 20 years and materials such as shellac, bitumen, modified bitumens and oil-manila gums are still used in large quantities.

Shellac still enjoys great popularity for the bonding of commutator separator plates, commutator V-rings and coil-slot wrappers. It is also used by some manufacturers for bonding the coil insulation of high-voltage stator coils for large generators.[17] When used with proper production technique, shellac bonds give excellent results and the reliability of the bond has been proved by at least 40 years of regular use by some manufacturers.

Bitumen bonds[2,5,16,19,20] and modified bitumen bonds[11] are used to a larger extent than shellac by the manufacturers of large generating equipment. The opinion is held by some engineers that a shellac bond is unsuitable for large machines, owing to the steeply rising dielectric-loss/temperature characteristics and comparative brittleness of shellac-bonded mica, which thus introduces the risk of insulation fracture under such fault conditions as short-circuits near the machine. These objections to shellac are heavily outweighed by the excellent results obtained by several manufacturers,[17] who still use shellac bonds for the insulation of, for example, turbo-generators up to at least 40 MW at 11 kV.

Some troubles have been experienced in service in America with bituminous-bonded mica-insulated turbo-alternator stator coils, owing to a phenomenon known as 'tape separation'.[11] This appears to take the form of a non-reversible longitudinal movement of the stator-coil insulation caused by heating and cooling of the windings. Opening-up of the coil insulation has been reported in some cases, although it is understood that no machine failures have occurred from this trouble.

The use of synthetic bonds and coil impregnants in the United States has been described by Laffoon.[11] These materials are of the polyester type. The use of bonds and impregnants of this type is a logical step from the use of bituminous bonds and impregnants and the results claimed represent a very distinct technical advance. No doubt the choice of the most suitable type of polyester and the balance between mica and bond content has been the culmination of considerable research. The

impregnation of stator coils with synthetic resins is a step in the direction of obtaining the complete filling of all voids in the mica insulation, and this may ultimately lead to an increase in the safe maximum working stresses in high-voltage coil insulations, with a resultant decrease in insulation thickness.

In the field of low-voltage machines mention has been made of a vinyl bond for commutator separator micanite and for moulded micanite V-rings.[71] It is claimed that the vinyl bond gives great mechanical stability of the micanite and thus greater mechanical stability of the commutator.

SLOT INSULATIONS

The use of mica-composite slot liner materials was almost universal for industrial motors before the 1939-45 war. Such liners are still used by some manufacturers for class-A machines. Many manufacturers to-day use slot liners which contain no mica.

Multi-ply Materials

A material which has proved to be highly satisfactory for slot liners of small motors is a 2-ply material consisting of varnished cotton cloth bonded to pressboard or leatheroid. Such material combines the good dielectric properties of the varnished cloth with the mechanical robustness of the pressboard or leatheroid.

Mica-composite liner materials are very variable in their dielectric properties and suffer marked damage when bent for insertion into small stator slots. It is probable that in some cases the mica content of the composite liner serves no really useful function, owing to damage done to the mica in forming the liner. Two-ply material, on the other hand, is much more robust and the breakdown level of inserted 2-ply liners is much more consistent than that of mica composite liners.

Two-ply slot insulation is also much more consistent in thickness than mica composite material; this is a most important factor in the easy winding of small machines. Two-ply insulation is also cheaper than mica-composite material of the same nominal thickness. The construction and properties of typical 2-ply and mica-composite slot insulations are given in Table 5.

For heavier windings, 3-ply insulation may be used in which the varnished cloth is sandwiched between two thicknesses of pressboard or leatheroid.

Cellulose Triacetate[72]

During the 1939-45 war considerable use was made of cellulose triacetate in Germany to replace

Table 5

CONSTRUCTION AND PROPERTIES OF SLOT INSULATIONS

Material	Construction	Average thickness	Coefficient of variation	Average instantaneous breakdown strength	Coefficient of variation
		mils	%	kV	%
Two-ply	10 mils pressboard 10 mils varnished-cotton cloth	22	5	7	10
Mica composite	5 mils pressboard 3 layers mica splittings 12 mils cotton cloth	25	13	10	15
Three-ply	5 mils pressboard 2 mils cellulose triacetate 5 mils pressboard	12	3·5	9·5	4·5
Three-ply	9 mils pressboard 2 mils cellulose triacetate 9 mils pressboard	20	3	9·5	4·5

All tests were performed with the British Standard 3-in and 1½-in diameter electrodes.

mica, which was scarce.[6,17] Two-ply or 3-ply slot liners made with triacetate film and press-board or leatheroid are very satisfactory for low-voltage machines ($\geq$ 1 kV). The performance of cellulose triacetate at temperatures up to 120° C is good and the film could be used in industrial class-B machines and is used in such machines manufactured on the Continent. The construction and properties of typical Continental 3-ply materials are given in Table 5.

Unfortunately, unplasticized triacetate film is not available in Britain, and the plasticized film is inferior in performance at high temperatures, owing to shrinkage and embrittlement. The plasticized film is suitable for class-A machines, but difficulties arise from the varnish treatment processes to which the windings are subjected. Synthetic-resin varnishes usually require a temperature of at least 130° C to obtain optimum curing, and heating at this temperature has an adverse effect on the plasticized film.

Continental 2-ply liner material incorporating unplasticized triacetate film has been subjected to varnish-treatment processes involving stoving temperatures as high as 170° C for one hour without any serious deterioration.

Varnished Pressboard

Ordinary cellulose-acetate film bonded to press-board is of very little value in the insulation of machines, as the acetate film shrinks considerably at temperatures much above 70° C and even varnish treatment processes using oleo-resinous varnishes which are stoved at 100° C will cause serious shrinkage and render the film useless. However, if the cellulose acetate is sprayed or knife-spread on to pressboard backing, the coated material will withstand quite extended stoving at 130° C and short stovings at 170° C with surprisingly little damage.

Cellulose-acetate-coated pressboard is successfully used by some manufacturers for slot liners in small motors, but the use of such material in machines which have to operate under severe tropical conditions must be viewed with some caution. A typical knife-spread cellulose-acetate-coated pressboard has a thickness of 17·5 mils and an average instantaneous breakdown strength of 8·5 kV, the coefficients of variation being 2% and 11%.

IMPROVED WOOD

Synthetic-resin-impregnated compressed laminated wood[73] has proved of marked value in the construction of the windings of large machines. Packing blocks, coil supports and spacers made of this material are very robust and the material can be machined to accurate shapes with an excellent finish. The material shows no significant shrinkage under service conditions and owing to its much higher thermal conductivity than ordinary hardwoods shows much less tendency to char when in contact with coils operating at elevated temperatures.

Generally, this class of material is more economical and more adaptable than phenolic paper or fabric laminates in thicknesses greater than $\frac{3}{4}$ in. Some of the packing blocks and coil supports used in large machines may be in thicknesses up to 2 in.

When used for components which are highly stressed continuously, impregnated laminated wood needs careful design. The endurance limit of the material under cyclic stresses at ordinary room temperature is less than half of its ultimate cross breaking strength.[74] At a temperature of 90° C the ultimate cross breaking strength is approximately 60% of that at room temperature. The Izod impact strength of the material at room temperature is not high, but its performance under impact loading in service is very much better than is indicated by the Izod impact value. It appears to have a high damping capacity.

The material has a greater tendency to warping than phenolic paper laminates, but this is not of great importance when it is used in thick sections.

In general, the electrical properties of the material are somewhat inferior to those of phenolic paper laminates (B.S.1137: 1949, type 2),[46] but they are more than adequate for applications such as packing and coil supports.

The more usual laminated wood consists of beech ply, but birch and poplar are sometimes used, although poplar does not appear to be sufficiently reliable. The laminated wood is normally impregnated and bonded with phenolic resins. The properties of a typical phenolic laminated beech-ply board are given in Table 6.

Table 6

MECHANICAL AND ELECTRICAL PROPERTIES OF PHENOLIC LAMINATED BEECH-PLY BOARD HAVING THE GRAIN OF ADJACENT LAMINATIONS AT RIGHT-ANGLES

Tensile strength	14,000–16,000 lb/in²
Compression strength, flatwise	30,000–35,000 lb/in²
Cross breaking strength	14,000–16,000 lb/in²
Impact strength, unnotched Izod test	3–4 ft/lb
Electric strength at room temperature	90–100 volts/mil

SILICO-ORGANIC MATERIALS

The introduction of the silicone materials in 1938 caused much interest in the electrical engineering world, owing to the good performance at high temperatures which was claimed for this class of materials. It was soon apparent that some of the early claims were somewhat exaggerated and it was some time before a proper assessment was made of the real value of the materials. Silico-organic chemistry is still in its infancy, but it seems certain that such materials will have a very wide use in the future. The cost of the materials at present makes their use unattractive in many cases.

It should be borne in mind that the up-rating of existing designs of machines presents problems other than those concerned with the insulation. This matter was very clearly dealt with by Alger and Jones.[75]

Insulating Varnishes[76-78]

Quite a wide range of silicone insulation varnishes are produced, including coil-impregnating varnishes, laminating varnishes, and mica-building varnishes. The coil varnishes are not difficult to use, but high stoving temperatures are necessary to obtain the best results. The silicone varnish having the greatest resistance to heat needs stoving at 250° C for many hours to obtain sufficient hardness and moisture resistance. A silicone varnish with a lower heat resistance requires stoving at at least 180° C for several hours to obtain satisfactory results. This particular type of varnish is suitable for class-H machines operating with a hottest-spot temperature of 180° C. It is preferable to stove the varnish at a temperature higher than the estimated maximum service temperature at which the machine has to operate.

Some of the silicone varnishes make excellent bonds for mica sheet, particularly flexible sheet, and in some cases the excellent mica-bonding characteristics are of value in the construction of machines operating at class-B temperatures. Silicone varnishes can be used for bonding moulded micanite components, but care is needed in manufacturing such mouldings. Excess moulding pressure can cause a serious degree of 'spew' of the bond, so that the resulting moulding is insufficiently well bonded.

Silico-organic Elastomers

The use of silicone elastomers in combination with glass textiles for the insulation of traction-motor field coils has been described by Reed and Tyner[79] and others.[80] The material may be in the form of glass tape coated with semi-cured elastomer, in which form the elastomer acts as a pressure-sensitive adhesive. After application of the tape the coil is stoved so as to complete the cure of the elastomer. The resulting coil has excellent moisture resistance and it has been claimed that the rating of the coil may be improved by this technique. Coils have been made where the elastomer-coated glass forms a covering over the normal mica tape and also where the elastomer-coated glass forms the entire insulation of the coil.

The silicone elastomers are certainly satisfactory for continuous operation at 180° C. It has been claimed that the material may be operated satisfactorily at temperatures higher than this, but the claim should be treated with some reserve.

Early silicone elastomers had a low tear strength and were somewhat 'cheesy', but the modern elastomers are almost as tough and tear-resistant as rubber. Satisfactory cables[81] can be produced with silicone-elastomer insulation and are suitable for continuous operation at 180° C. These fill the long-felt need for a cable for high-temperature machines, as the electric strength of the insulation is almost as good as that of rubber cables.

FLUORCARBONS[82]

Some very interesting fluorcarbons polymers were produced some years ago in the United States. They were not intended primarily as insulating materials, but have found considerable application as such in recent years. The materials dealt with below are particularly interesting because of their phenomenal resistance to heat.

Table 7

MECHANICAL AND ELECTRICAL PROPERTIES OF POLYTETRAFLUORETHYLENE AND POLYCHLORTRIFLUORETHYLENE

Material	Tensile strength	Elongation	Compression strength at 0·1% deformation	Electric strength at room temperature		Volume resistivity	Permittivity	Specific gravity
				Short-time test	Long-time test			
	lb/in²	%	lb/in²	volts/mil		ohm-cm		
Polytetrafluor-ethylene	2,000–4,500 (may be as high as 15,000 with oriented film)	300–400	1,600–1,800	>1,000 (5 mils thick)	<150	10^{16}	2	2·1–2·3
Polychlortri-fluorethylene	8,000–10,000	120–130	—	> 1,000 (5mils thick)	—	5×10^{17}	2	2·1

Polytetrafluorethylene[83, 84]

The characteristics of polytetrafluorethylene (p.t.f.e.) have been dealt with in some detail in the technical Press. For use in electrical machines the material is mainly of interest in the form of film and as a wire enamel, and Table 7 gives its mechanical and electrical properties.

Films at least as thin as 0·5 mil are manufactured. The material has high tensile strength and resistance to tearing and lends itself to neat, tight taping of armature coils, etc. The short-time electric strength of the film is very high and the use of the material for machine insulation was considered to be very promising. Unfortunately it is unusually sensitive to electrical discharges and it was soon found that the long-time electric strength of taped insulation was less than 150 volts/mil. It is possible that suitable impregnation of tape-applied insulation would raise the voltage endurance of the material, but the impregnation would have to be such that complete filling of all voids was achieved; this is, of course, exceptionally difficult in practice. A further difficulty in achieving complete impregnation is the fact that there are very few substances which will adhere to p.t.f.e.

Polytetrafluorethylene suffers from rather exaggerated cold flow, and the mechanical stress on the insulation must be very low if plastic flow is not to take place. This plastic flow can be reduced somewhat by reinforcing the p.t.f.e. insulation with glass textiles. Glass can be coated with p.t.f.e. quite successfully and such a material is used for slot liners in low-voltage machines to some extent. Table 8 gives some of the mechanical and electrical properties of this material.

Table 8

MECHANICAL AND ELECTRICAL PROPERTIES OF P.T.F.E.-COATED GLASS FABRIC 5 MILS THICK

Tensile strength, warp direction	100 (minimum) lb/in
Short-time electric strength at room temperature	> 500 volts/mil
Long-time electric strength	< 150 volts/mil
Volume resistivity	5×10^{11} ohm-cm
Permittivity	3
Maximum service temperature (continuous)	250° C.

Wire can be enamelled with p.t.f.e. using an emulsion technique.[85–87] The covering is very tough and quite a thin coating can be applied. The plastic flow of p.t.f.e. becomes a real embarrassment in such cases and the successful use of p.t.f.e. enamelled wire in armature windings, for example, is fraught with difficulties.

Polytetrafluorethylene is considered to be suitable for continuous operation in service at 250° C. It is claimed[82] that p.t.f.e. still shows some toughness at —200° C.

Polychlortrifluorethylene[88]

From a general point of view polychlortrifluorethylene (p.c.t.f.e.) is somewhat similar to p.t.f.e., and some of its properties are given in Table 7. Its resistance to heat is inferior to that of p.t.f.e., but it has the great advantage of being much easier

to mould and extrude. The maximum continuous operating temperature for p.c.t.f.e. is claimed to be 200° C. It is considerably more expensive than p.t.f.e., so that interest in it is mainly academic at present so far as its use in machines is concerned, although some work has been done with wire enamelled with suspensions of the resin; the covering is very robust and it does not suffer so much as p.t.f.e. so far as plastic flow is concerned.

MISCELLANEOUS NEW MATERIALS

There are numerous new materials which have so far received comparatively little attention in Britain. Some of the more interesting are mentioned below.

Mica Paper (Exfoliated Mica)[89-91]

Bardet, in France, developed a method of reducing mica to a coarse powder and making it up into a paper-like film. In general terms, the process produces nascent surfaces on the small mica flakes and they can then be made to adhere together without the addition of any resinous bond. The mica paper is rather weak mechanically, but it is strong enough to enable it to be handled in paper-making machines. By adding suitable bonds or backing materials such as silk or woven glass cloth, hard mica plates or flexible mica films can be produced.

Hard exfoliated mica plates bonded with shellac or silicone resin can be made to fine tolerances without sanding. The flexible mica tape can also be produced with much finer tolerances than are possible with the usual mica tapes made with mica splittings. It is understood that resin-bonded pressed sheets can be produced to a thickness tolerance of less than ± 1 mil on a nominal thickness of 32 mils and below, and ± 1.2 mils on nominal thicknesses greater than 32 mils; it is also understood that these fine tolerances are met without sanding. Ordinary commutator micanite to B.S.626: 1946 is supplied to a thickness tolerance of $\pm 1{\cdot}3$ mils, but sanding is necessary to meet this tolerance.

The short-time electric strength of silicone-bonded exfoliated mica is claimed to be of the order of 1,900 volts/mil for an 18-mil sheet and 1,200 volts/mil for a 32-mil sheet. The voltage endurance of resin-treated exfoliated mica appears to be almost as good as that of normal micanite materials.

Exfoliated mica would appear to have considerable potential use, but long-time studies are necessary before the material can be adopted with confidence.

High-temperature Dielectrics[93,94]

Some interesting results have been obtained with organo-boron resins. It is suggested that boron-phosphorous combinations may be suitable for service temperatures higher than 400° C for short periods. They appear to show excellent thermal stability in the range 300-400° C.

Derivatives of perfluoroacetonitrile and also perfluoroacetylene appear to be capable of high-temperature operation.

Mention has been made of rigid plastics derived from polybutadiene with continuous stability up to 200° C. These materials can also be used in glass-fabric laminates. It is suggested that such laminates compare favourably with silicone-bonded-glass fabric laminates.

CONCLUSIONS

Many interesting developments have taken place during the last 25 years, and design and insulation engineers have not been slow to adopt new materials. The practice of some insulation manufacturers of depending on the user to carry out all the experimental work on new or improved materials is deplored, and the electrical manufacturing industry would be helped very considerably if more of the insulation manufacturers gave reliable technical information on their products.

The use of some of the more recent insulation materials such as the terephthalic polyester textiles, the polyamide textiles and the polyester or ethoxyline resins is restricted to some extent by the existing British Standard classifications of insulation. This matter is receiving active consideration and it is to be hoped that it will not be long until the classifications are modified in a way which will permit greater freedom of choice of materials.

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